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RETIREMENT OF MR M. H. FREEMAN, O.B.E.

Mr M. H. Freeman, Deputy Director (Forecasting), retired from the Meteorological Office on 31 December 1975, a few months before his sixtieth birthday. He graduated from King's College, London in 1937, with a first class honours degree in mathematics and, after obtaining a teaching diploma, taught until the early days of the Second World War when in April 1940 he joined the Meteorological Office as a Temporary Forecaster. Following initial training he was posted to Headquarters No. 11 Group Royal Air Force at Uxbridge in August 1940 at the height of the Battle of Britain and he remained in that busy and responsible forecast office for six years. He obtained his Master of Science degree in Meteorology at Imperial College, London in 1944.

After the war Mr Freeman was established as a Senior Scientific Officer and served for two years in charge of the forecast office in Khartoum. On return to England in 1948 he had a short spell at the newly created London Airport at Heathrow followed by over three years in the Civil Aviation Branch at Headquarters. In 1953 he was promoted to Principal Scientific Officer and was meteorological observer at the first tests of the British atomic bomb in Australia. He had short periods at Bawtry and as a senior forecaster in the Central Forecasting Office at Dunstable and was then assigned as Meteorologist for the tests of the hydrogen bomb at Christmas Island in 1957; his achievements in this post were recognized by his appointment as an Officer of the Order of the British Empire in the following year.

Between 1958 and 1963 Mr Freeman was engaged in research into forecasting, first in the Synoptic Research Branch and later in the Techniques and Training Branch. After a few months on the Senior Forecaster roster in the Central Forecasting Office, by now at Bracknell, he was promoted in 1963 to the post of Assistant Director (Synoptic Climatology) where one of his early tasks was the issue for the first time to the general public of the *Monthly Weather Survey and Prospects*.

In 1966 he became Chief Meteorological Officer at London (Heathrow) Airport, returning to Headquarters, Bracknell, in 1970, as Assistant Director (Public Services). In 1971 he was transferred as Assistant Director (Special Investigations) and on promotion in 1972 he became Deputy Director (Communications and Computing), becoming Deputy Director (Forecasting) in September 1973.

Howarth Freeman has always had a practical, logical bent and the Office recognized this and made good use of his special talents. He was a sound and successful synoptic forecaster for many years and was specially chosen to cope with the new meteorological problems associated with the atomic and hydrogen bombs. He introduced computer-aided forecasts for aviation purposes when he was at Heathrow in the late sixties and later he made a special survey of the forecasting service for the Royal Air Force which led to considerable streamlining. He was never afraid of change and was always seeking to improve. He was widely known within the Office and his cheerful friendly personality will be missed by his colleagues.

We all wish him and Mrs Freeman a long and happy retirement.

J. K. BANNON

551.501.9 : 551.508.77 : 681.2.08

COMPARISON OF THE CATCH OF GROUND-LEVEL AND CANOPY-LEVEL RAIN-GAUGES IN THE UPPER SEVERN EXPERIMENTAL CATCHMENT

By ANNA J. NEWSON and R. T. CLARKE
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SUMMARY

This note describes the results of statistical analyses comparing the monthly catch of ground-level rain-gauges with that of canopy-level gauges in the Institute of Hydrology's experimental catchment in the headwaters of the River Severn. The results suggest that, for all months free of snowfall, there is no evidence that the canopy-level gauges catch significantly less than those at ground level, as had been feared; for months when an appreciable part of the precipitation fell as snow, however, there was evidence that canopy-level gauges caught significantly less than ground-level gauges.

INTRODUCTION

The investigation by the Institute of Hydrology, currently in progress on the headwaters of the Wye and Severn catchments in mid Wales, into the hydrological differences between coniferous forest and hill pasture, required a measurement of the precipitation over the forest canopy of the Severn for comparison with that over the hill pasture of the Wye; about one-third of the Severn is also unforested. For the Wye, and for the unforested area of the Severn, precipitation was measured using Octapent (Mk 2A) gauges installed at ground level in square pits, surrounded by a 1·33-metre square plastic grid to prevent splash, and set with the gauge orifice in the tangent plane to the slope (Rodda, 1968). For the forested part of the Severn, the gauges chosen were mast-top canopy-level gauges, each consisting of a sheet-copper funnel with the standard 5-in (127·0-mm) diameter with a slant length of 3·5 in (88·9 mm) feeding into a copper tube $\frac{1}{2}$ in (12·7 mm) in diameter, mounted with the funnel rim horizontal on a vertical mast. Polythene tubing connects the funnel to the base collector, a modified period gauge with firmly fitting lid. All gauges are read monthly. The mast-top gauges are installed in the forest with their funnels at mean canopy level or above. The trees (mainly Sitka spruce) range in height from 3 m to 16 m.

The rain-gauges in the Severn and Wye networks were distributed according to the proportion of catchment area falling into categories or 'domains', delimited by four divisions of altitude, four of aspect and three of slope. For the purposes of this note the Severn catchment only need be considered; the divisions of altitude, aspect and slope used to delimit the domains are as follows:

Altitude (metres)	320–424 (code A)
	425–529 (code B)
	530–634 (code C)
	635–740 (code D)
Slope (degrees)	0–9 (code 1)
	10–19 (code 2)
	⩾20 (code 3)
Aspect	North-easterly (code W)
	South-easterly (code X)
	South-westerly (code Y)
	North-westerly (code Z)

Of the 116 homogeneous elements of area into which the Severn was divided (making up 32 different combinations of domain criteria out of a possible 48) only those contributing more than 2 per cent of the total area of the catchment contain a gauge placed at random. There are 18 period gauges in all in the Severn network, representing 17 domain combinations; 7 are at ground level and 11 at canopy level. The numbers of ground-level and canopy-level gauges in each altitude division are as follows:

	Altitude division				
	A	B	C	D	Total
	Number of gauges				
Ground level	0	2	2	3	7
Canopy level	5	3	3	0	11
Total	5	5	5	3	18

Analysis

Earlier analysis (Clarke *et alii*, 1975) of the catch recorded by monthly storage gauges on the Wye and Severn had shown that catch varied significantly with altitude division (gauges in the higher-altitude divisions recording greater falls than those in lower altitude divisions); there was no evidence, however, that catches by gauges in different slope divisions, or in different aspect divisions, differed significantly. For the analysis described in this note, therefore, altitude effects were retained in the statistical model, but aspect and slope effects were assumed negligible.

The statistical model used was as follows. Consider the catch in a particular month by a gauge in altitude division i (where i = A, B, C or D). If μ is the true areal mean precipitation for the entire catchment, the catch by the gauge in division i will deviate from μ by an amount a_i which measures the extent to which gauges in that altitude division tend to catch more (or less) than the true areal mean. Clearly the sum of the a_i over all the gauges in the network must be zero, because the areal mean is μ. The gauge under consideration may be either a ground-level gauge or a canopy-level gauge, and if the possibility of differential catch is admitted, a term l_j must be included with $j = 1, 2$ (l_1 is the deviation from the areal mean μ appropriate to ground-level gauges, whilst l_2 is that appropriate to canopy-level gauges). The quantities l_j therefore

measure the differential effect of gauge 'level'; as before, the sum of the l_j over all the gauges in the network must be zero. The effects on catch of altitude differences between ground-level and canopy-level gauges in the same altitude class (A, B, C or D) are assumed negligible. Finally, if there are several gauges in a particular altitude division all of which are, say, at ground level, then the catch by the kth gauge (y_{ijk}) will deviate from $\mu + a_i + l_j$ by a quantity ϵ_{ijk} which is regarded as a random variable. The complete model is therefore

$$y_{ijk} = \mu + a_i + l_j + \epsilon_{ijk} \; (i = \text{A, B, C, D}; j = 1,2)$$

$\Sigma a_i = \Sigma l_j = 0$, where summation is over all gauges in the network.

Linear statistical theory was used to test the hypothesis that catches by ground-level and canopy-level gauges do not differ, except for random variation. (In the terminology, the null hypothesis is given by H_0: $l_1 = l_2 = 0$, to be tested against the alternative hypothesis H_1: l_1, $l_2 \neq 0$). The calculation is best set out in tabular form in which the total sum of squares of deviations from the estimated arithmetic mean $\bar{\mu}$ for the whole catchment is divided into three components: one corresponding to differences between altitude divisions, ignoring the effects of differences between levels; another corresponding to differences between levels, eliminating the effects of differences between altitude divisions; and a third yielding an estimate of the variance of residuals ϵ_{ijk}. The analysis-of-variance table therefore appears as follows:

		d.f.
(A)	Between altitude divisions (ignoring levels)	3
(L)	Between levels (eliminating altitude effects)	1
	Residual	13
	Total	17

The null hypothesis of no difference between levels is tested by comparing the ratio (mean square between levels, eliminating altitude effects/residual mean square) with tabulated values of the F-statistic with 1 and 13 degrees of freedom (d.f.).

In addition, the statistical model used above ($y_{ijk} = \mu + a_i + l_j + \epsilon_{ijk}$) was modified to test whether the differences in catch between ground-level and canopy-level gauges varied between altitude divisions (i.e. whether a significant interaction existed between altitude and level). Since the lowest altitude division, A, contained no ground-level gauge and the highest altitude division, D, contained no canopy-level gauge, the analysis was confined to altitude divisions B and C. The modified model becomes

$$y_{ijk} = \mu + a_i + l_j + (al)_{ij} + \epsilon_{ijk};$$

where a_i ($i = 1,2$) and l_j ($j = 1,2$) are constants measuring the altitude and level effects respectively, and the interaction terms $(al)_{ij}$ measure the extent to which level differences vary with altitude. As before, the null hypothesis H_0: $(al)_{ij} = 0$ for all i,j was tested against the alternative H_1: $(al)_{ij} \neq 0$ by means of a variance ratio test using an analysis of variance table. Since there were two ground-level gauges, and three canopy-level gauges, in each of the altitude divisions B and C, the analysis of variance is that appropriate to a two-by-two classification (level times altitude) with proportional numbers in

the sub-classes; for any one month, therefore, the total variation amongst the ten gauges was divided as follows:

		d.f.
(A)	Between altitude divisions	1
(L)	Between gauge levels	1
(AL)	Interaction	1
	Residual	6
	Total	9

The test for the hypothesis of no interaction is made by comparing the variance ratio (interaction mean square)/(residual mean square) with tabulated values for 1 and 6 degrees of freedom.

Results

Table I shows the values of the 'level' constants l_1,l_2 (free from altitude effects) obtained month by month for the period April 1971–March 1973, together with the arithmetic mean for all 18 gauges. In 13 of the 24 months, ground-level gauges caught more than the overall mean (since the values of l_1 were positive in 13 months of the 24); in the remaining 11 months they caught less. On average, over all 24 months, ground-level gauges caught 2·8 mm more than the monthly mean (174·4 mm) and the canopy-level gauges caught 1·8 mm less

TABLE I—PARAMETERS l_1,l_2 REPRESENTING THE DIFFERENCE BETWEEN GROUND-LEVEL AND CANOPY-LEVEL GAUGE CATCH, APRIL 1971–MARCH 1973

	Mean, all gauges	Ground level (l_1) *millimetres*	Canopy level (l_2)	Snow days, Moel Cynnedd†
Apr. 1971	71·2	+0·8	−0·5	0
May 1971	75·2	+2·1	−1·3	0
June 1971	192·4	+2·4	−1·6	0
July 1971	71·1	+1·2	−0·7	0
Aug. 1971	217·8	−1·3	+0·8	0
Sept. 1971	89·7	+1·5	−1·0	0
Oct. 1971	211·2	+6·9	−4·4	0
Nov. 1971	307·9	+8·9	−5·7	7
Dec. 1971	127·9	−0·6	+0·4	3
Jan. 1972	227·6	+10·1	−6·4	8
Feb. 1972	145·9	+18·6*	−11·8*	6
Mar. 1972	213·2	+21·1*	−13·4*	3
Apr. 1972	301·2	+18·8	−12·0	0
May 1972	145·8	−6·5	+4·1	0
June 1972	198·1	−15·9	+10·1	0
July 1972	141·0	−6·4	+4·1	0
Aug. 1972	123·8	−5·0	+3·2	0
Sept. 1972	62·0	−2·4	+1·5	0
Oct. 1972	81·1	−1·6	+1·0	0
Nov. 1972	328·5	−3·5	+2·2	1
Dec. 1972	254·8	−5·5	+3·5	1
Jan. 1973	176·4	+5·7	−3·6	4
Feb. 1973	283·4	+26·7*	−17·0*	9
Mar. 1973	138·6	−8·4	+5·4	1
Overall mean	174·4	+2·8	−1·8	
Mean, months when snow fell	220·4(10)	+7·3	−4·6	
Mean, months when no snow fell	141·5(14)	−0·4	+0·2	

* Denotes statistical significance ($P < 0{\cdot}05$). † National Grid Reference SN 843877.

($7 \times 2{\cdot}8 + 11 \times -1{\cdot}8 = 0$, apart from rounding error). Because no test for the significance of the altitude effects is possible using the analysis at present under discussion, the altitude constants a_A, a_B, a_C, a_D are not set out in Table I. This table also shows that significant ($P < 0{\cdot}05$) departures from zero of the level constants, l_1 and l_2, occurred in only 3 months of the 24 (February and March 1972, February 1973). All three were months when snow fell at Moel Cynnedd, a daily meteorological station in the Severn catchment: Table I shows the number of days on which snow fell there. If means are taken over all months when snow fell, gauges at ground level caught 7·3 mm more precipitation over a month than the mean for all gauges and those at canopy level about 4·6 mm less (Table I). Differences between ground-level and canopy-level gauges were much less evident in snow-free months when, on average, ground-level gauges caught about 0·4 mm less and canopy-level gauges about 0·2 mm more, than the mean for all gauges.

Results of the second part of the analysis, which had as its objective a test of whether differences between catches of ground-level and canopy-level gauges varied with altitude, are shown in Table II. A significant interaction was found

TABLE II—MEAN SQUARES FROM ANALYSIS OF VARIANCE TABLES FOR TESTING SIGNIFICANCE OF 'INTERACTION' BETWEEN ALTITUDE AND GAUGE-LEVEL, APRIL 1971–MARCH 1973

	d.f.	April 71	May 71	June 71	July 71	Aug. 71	Sept. 71
A	1	4·90	103·68*	1582·56	264·20	1020·10	370·88*
L	1	4·48	27·61	38·24	8·44	10·17	15·20
AL	1	11·27	11·35	176·47	34·81	19·84	0·05
Residual	6	35·88	11·05	497·54	49·57	237·60	57·45
Mean		71·48	76·44	201·48	72·20	222·96	93·49
CV		8·4%	4·3%	11·1%	9·8%	6·9%	8·1%
	d.f.	Oct. 71	Nov. 71	Dec. 71	Jan. 72	Feb. 72	Mar. 72
A	1	138·38	208·85	0·48	1904·40	851·93	372·10
L	1	306·00	512·75	2·20	656·70	2225·29*	2862·12*
AL	1	505·18	17·50	38·56	2350·00*	846·75	620·82
Residual	6	626·87	1156·61	197·40	214·92	279·47	288·32
Mean		213·80	309·03	130·00	224·00	127·23	202·28
CV		11·7%	11·0%	10·8%	6·5%	13·1%	8·4%
	d.f.	April 72	May 72	June 72	July 72	Aug. 72	Sept. 72
A	1	8323·23*	165·65	302·50	571·54	197·14	26·57
L	1	2266·89	268·82	1619·28	265·02	160·07	35·88
AL	1	317·41	17·71	456·50	13·35	3·36	9·13
Residual	6	1099·63	181·97	695·66	168·48	83·05	6·32
Mean		308·31	147·55	205·86	146·38	128·00	62·87
CV		10·8%	9·1%	12·8%	8·9%	7·1%	4·0%
	d.f.	Oct. 72	Nov. 72	Dec. 72	Jan. 73	Feb. 73	Mar. 73
A	1	384·40*	4481·69*	112·90	535·82	232·32	1·68
L	1	15·71	79·12	197·29	211·31	4592·00*	459·27
AL	1	4·54	1·39	212·06	80·27	180·61	98·30
Residual	6	34·18	529·88	564·54	905·39	449·58	399·82
Mean		82·26	333·07	263·44	186·42	284·48	137·85
CV		7·1%	6·9%	9·0%	16·1%	7·4%	14·5%

* Denotes statistical significance $P < 0{\cdot}05$.

Note. An explanation of A, L and AL is given in the text (see page 4).
CV is the coefficient of variation, d.f. means degrees of freedom.

only in January 1972. This could well be due to chance: when a large number of significance tests are made at the $P = 0{\cdot}05$ significance level, approximately one test in twenty will suggest that real differences exist even when this is known to be false. Here, we have found but one significant interaction in 24 independent tests, a proportion agreeing well with what could be expected if no interaction existed. It would not be incorrect to conclude, therefore, that such interaction as does exist between level and altitude is probably small.

Discussion

The difficulties associated with measurement of precipitation over a forest have long been recognized (Mill, 1900) and a comprehensive review of the problem has been given by Penman (1963). In a more recent contribution, Clarkson (1973) studied the performance of a tulip-shaped rain-gauge funnel mounted on a 10-m mast, concluding that it collected 98·4 per cent of the catch of a standard Mk 2 rain-gauge nearby. The results of the present analysis, comparing the catches of two types of rain-gauge, show no evidence that canopy-level gauges caught significantly less than ground-level gauges in months free of snowfall. For months when an appreciable proportion of the precipitation fell as snow, however, there was evidence that the catch of canopy-level gauges differed from that of ground-level gauges; this may be because turbulence caused the canopy-level gauges to undercatch snowfall, or because snow drifting into the funnels of ground-level gauges caused them to overcatch. For water-balance calculations, therefore, the Institute is now measuring the input of precipitation as snowfall by means of ground-based photogrammetry (to give snow depth) together with snow-core sampling (to give snow density).

When comparing the effects of alternative land uses on the water balance, the problem of sampling precipitation over a range of topographic locations is frequently encountered; the problem is especially severe where the land-use under investigation is dense forest with few large clearings for conventional ground-based gauges. The above conclusions give room for optimism regarding the use of mast-top, canopy-level gauges for the measurement of precipitation over forest in those conditions where snowfall is not a significant component of catchment input.

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THE EFFECT OF TOPOGRAPHY ON SURFACE WIND

By D. M. GUNN and D. F. FURMAGE
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SUMMARY

Anemograph records from four valley stations in Scotland, where topography would be expected to influence materially the surface wind direction and speed, were studied in order to show the extent of such influence and whether a coherent pattern existed. Further, from these findings, an attempt was made to establish a method which might have general application in forecasting surface wind velocities in valleys.

INTRODUCTION

Ideally, an anemograph is exposed at a height of 10 metres above the ground in level, open terrain with no obstructions nearer than 200 metres in any direction. Although the immediate surroundings may satisfy these conditions, the surface wind can be affected by surrounding hills and valleys, particularly in mountainous areas such as those in Scotland.

For this study the records from anemographs on four sites where the topographical influence is considerable were used. Their locations are shown on the map in Figure 1 and details of the sites are given in Table I. Maps showing the local topography with contours at 500-ft (about 150-m) intervals are given in Figures 2 to 5. On each map a cross indicates the position of the anemograph.

TABLE I—DETAILS OF THE ANEMOGRAPH SITES

Station	National Grid Reference	Height of anemograph above MSL	Height of anemograph above ground
		metres	
Tummel	NN 772590	161	16
Shin	NH 573974	24	10
Rannoch	NN 423575	306	17
Fort Augustus	NH 356085	58	16

Because of the absence of local obstructions to the wind flow, the effective height for each anemograph is equal to the actual height above the ground.

The period covered was May 1966 to April 1967 for all geostrophic wind directions plus May 1967 to April 1968 for winds between 010° and 170° in order to increase the number of samples with easterly winds.

METHOD

The surface wind recorded at each site was compared with the geostrophic wind over the local region obtained from charts of mean sea-level pressure. Only geostrophic winds of 20 knots or more were considered as it was thought that at low geostrophic speeds any relationship between the surface wind and geostrophic wind would be masked by local effects, such as anabatic and katabatic winds. The geostrophic wind velocity was measured from daily synoptic charts on a scale of 1 : 7½ M, prepared at three-hourly intervals. Directions were estimated to the nearest 10° and speeds to the nearest 2 knots, closer accuracy not being justified with the scale of working charts used. The mean hourly wind velocity recorded at the anemograph station in the hour preceding the chart time was taken as the surface wind. Occasionally, because

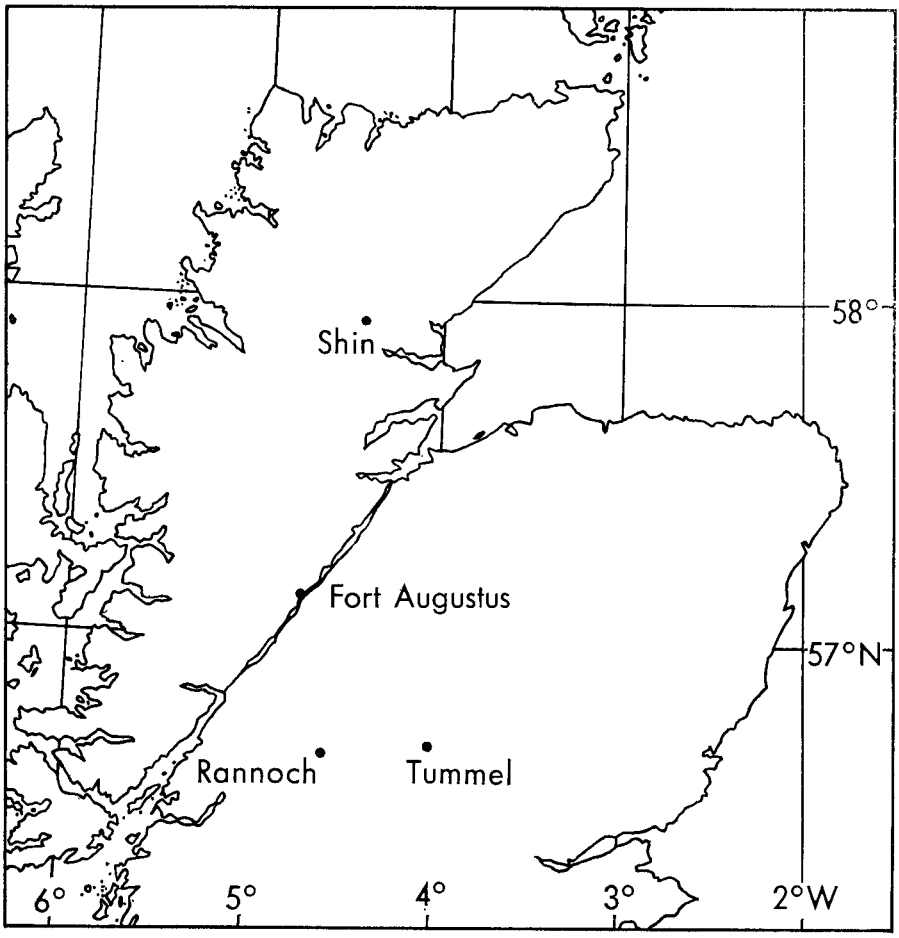

FIGURE 1—MAP SHOWING THE LOCATION OF STATIONS

there had been a change of direction in the surface wind during the hour, the mean value was considered unrepresentative and so was discarded. Values in the vicinity of fronts were also discarded.

Analysis

For each station the geostrophic and surface winds were tabulated for each hour. Irrespective of the hour, the data were classified according to the 36 geostrophic wind direction sets and the following information extracted for each set:

(a) The ratio of the mean surface wind speed to the mean geostrophic wind speed and the standard deviation of this ratio.
(b) The mean and standard deviation of the surface wind direction.
(c) Three-term running means (covering an angle of 30°) of the ratio of mean surface wind to mean geostrophic wind speed.

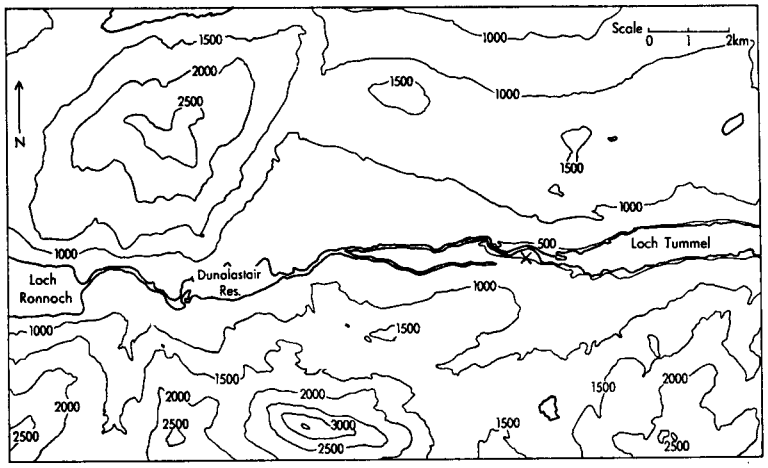

FIGURE 2—TOPOGRAPHY AROUND TUMMEL

Heights are in feet (1000 ft ≈ 305 m). The anemograph site is shown by a cross.

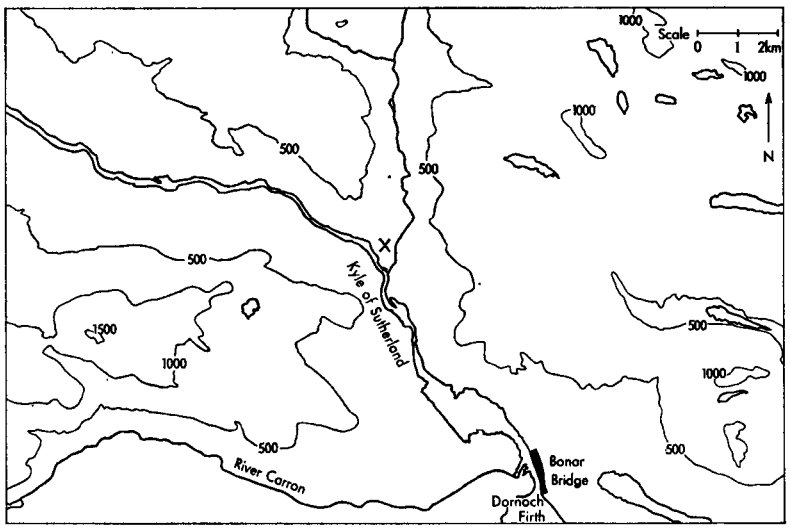

FIGURE 3—TOPOGRAPHY AROUND SHIN

See notes below Figure 2.

(d) Three-term running means (covering an angle of 30°) of the mean angle between the geostrophic and surface wind directions.

These results are shown graphically in Figures 6 to 9. The number of samples for each direction is entered on the curve (d) in each figure.

For each station the following information was determined:

(i) Backing of surface wind from geostrophic wind in the valley direction.

(ii) Geostrophic wind direction for minimum backing of surface wind.

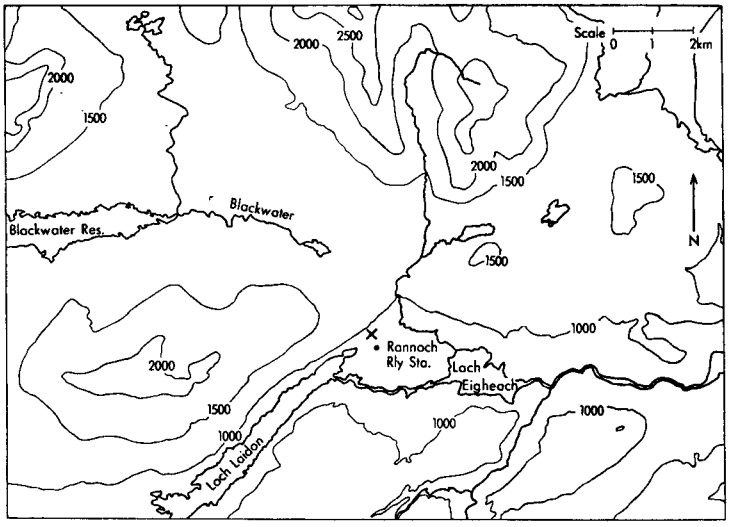

FIGURE 4—TOPOGRAPHY AROUND RANNOCH
See notes below Figure 2.

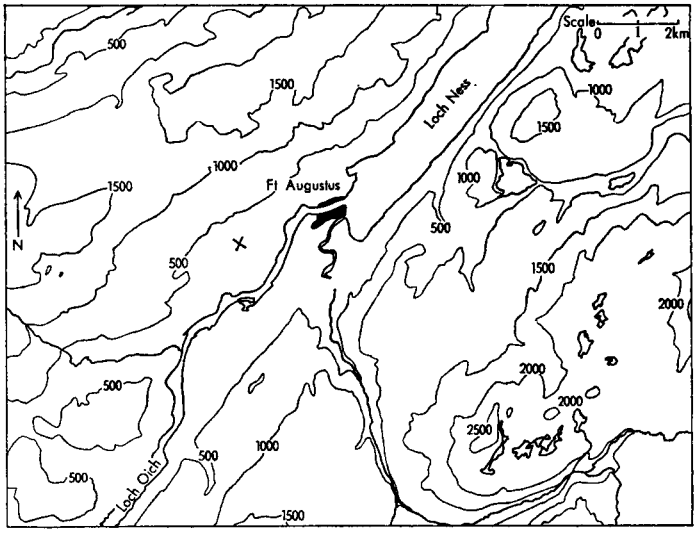

FIGURE 5—TOPOGRAPHY AROUND FORT AUGUSTUS
See notes below Figure 2.

(iii) Ratio of surface wind speed to geostrophic wind speed in the valley direction.
(iv) Geostrophic wind direction for maximum speed ratio.
(v) Backing of surface wind from geostrophic wind in the cross-valley direction.

(vi) Geostrophic wind direction for maximum backing of surface wind.
(vii) Ratio of surface wind speed to geostrophic wind speed in the cross-valley direction.
(viii) Geostrophic wind direction for minimum speed ratio.
(ix) Mean speed ratio for all geostrohpic wind directions.

These details are shown in Table II.

TABLE II—RELATIONSHIP OF SURFACE WIND TO GEOSTROPHIC WIND

	Tummel	Shin	Rannoch	Fort Augustus
Backing in valley direction	13° at 090° −1° at 270°	25° at 120° 26° at 300°	7° at 060° 0° at 240°	10° at 050° 1° at 230°
Minimum backing	9° at 100° −2° at 260°	17° at 100° 15° at 270°	7° at 060° −3° at 230°	2° at 020° −31° at 180°
Speed ratio in valley direction	15% at 090° 26% at 270°	34% at 120° 40% at 300°	49% at 060° 55% at 240°	35% at 050° 35% at 230°
Maximum speed ratio	28% at 140° 29% at 290°	36% at 130° 41% at 290°	50% at 070° 56% at 290°	35% at 050° 36% at 240°
Backing in the cross-valley direction	72° at 180° 64° at 360°	64° at 210° 62° at 030°	54° at 150° 47° at 330°	42° at 140° 77° at 320°
Maximum backing	73° at 170° 73° at 030°	64° at 210° 62° at 030°	54° at 150° 47° at 330°	56° at 110° 77° at 320°
Speed ratio in cross-valley direction	19% at 180° 24% at 360°	21% at 210° 23% at 030°	42% at 150° 46% at 330°	23% at 140° 21% at 320°
Minimum speed ratio	17% at 200° 13% at 080°	21% at 210° 21% at 040°	31% at 190° 36% at 010°	20% at 160° 16% at 350°
Mean speed ratio for all wind directions	21·5%	31·5%	42·0%	23·5%

Note. All directions are of geostrophic wind.

For the four sites a comparison was made between the average ratios of hourly maximum-gust speed to hourly mean speed for surface winds greater than 10 knots blowing across the valley and down the valley. The period covered was January 1973 to March 1974. The results are shown in Table III.

TABLE III—AVERAGE RATIOS OF HOURLY MEAN MAXIMUM GUST SPEED TO HOURLY MEAN SPEED

Station	Mean elevation of surrounding terrain	Cross-valley ratio	Down-valley ratio	Mean ratio over all directions
Tummel	4·6°	2·30	1·90	1·99
Shin	3·3°	1·95	2·07	1·96
Rannoch	1·7°	1·65	1·52	1·52
Fort Augustus	4·1°	2·05	1·78	1·83

Discussion

Because of friction at the earth's surface, the wind near the ground is reduced in speed and backed in direction when compared with the geostrophic wind. The reduction in speed and the amount of backing depend on a number of factors including the nature of the terrain, the geostrophic wind speed and the stability of the air (which may depend to some extent on wind direction). For geostrophic winds of 20 knots or more, the wind measured at 10 m above open level country is backed 20–25° from the geostrophic wind direction and the

ratio of the speed to that of the geostrophic wind is 0·4–0·5; in the absence of thermal wind effects these values do not vary much with geostrophic wind direction.

Figures 6–9 show how the presence of valleys distorts the flow, with the surface winds tending to blow along the direction of the valley. As might be expected from the topography, the effect is most pronounced at Fort Augustus. At this station the deviations between the directions of the geostrophic and surface wind vary from a backing of 80° to a veer of over 30° and with geostrophic wind directions from 180° to 320° the surface winds blow along the valley with very little deviation from its orientation of 230° (Figure 9 (b)). Tummel (Figure 6 (b)) also shows the funnelling effect very clearly with surface winds blowing quite steadily from 090° to 100° with all geostrophic wind directions from 090° to 180°. At Shin and Rannoch where the valleys are less well defined, the channelling is not so pronounced but clearly in evidence (Figures 7 (b) and 8 (b)).

The valley effect is also apparent in the ratios of surface wind speed to the geostrophic wind speed. Figures 6 (c)–9 (c) show that the ratio varies approximately twofold in the valleys under consideration, with maxima when the geostrophic wind directions are roughly in the valley directions and minima when geostrophic wind directions are mostly between 50° and 90° away from the valley directions. Exceptions to these generalizations occur, notably a minimum ratio at Tummel with a geostrophic wind direction of 080° which is almost the same as the orientation of the valley. The reasons for these discrepancies are probably to be found in the detail of local topography and in the sample of observations.

From Table 3 it can be seen that gustiness in cross-valley winds is higher than in along-valley winds at all stations except Shin, where the valley direction is least well defined. There is fair correlation between the average gust ratio and the mean elevation of the terrain around the anemometer site. The effect will of course be masked to an appreciable extent by local aspects of exposure and this appears to be the case at Shin where the down-valley ratio exceeds the cross-valley ratio.

Application to forecasting

Stability of the surface layer must affect the relationship between surface wind speed and direction and orographic features but it has been neglected in this study. Further work needs to be done on the combined effects of stability and topography. Also, local aspects of exposure might have considerable influence, particularly with lighter surface winds.

In spite of the shortcomings in the data, the results have sufficient coherence to suggest that some guidance can be given in forecasting winds in valleys. However, since the shapes of valleys vary so much, some simple parameter to compare one with another is required. One possible parameter is the mean elevation of the horizon around the site. This was determined for each of the four sites and the mean speed ratio for all wind directions plotted against it. The mean surface wind speeds at Tummel, Rannoch and Fort Augustus were adjusted to a common height of 10 metres by applying a factor of 0·9 to the mean of the recorded values. The result is shown in Figure 10. The ratios at the lower elevation seem a little high, perhaps because they are unduly

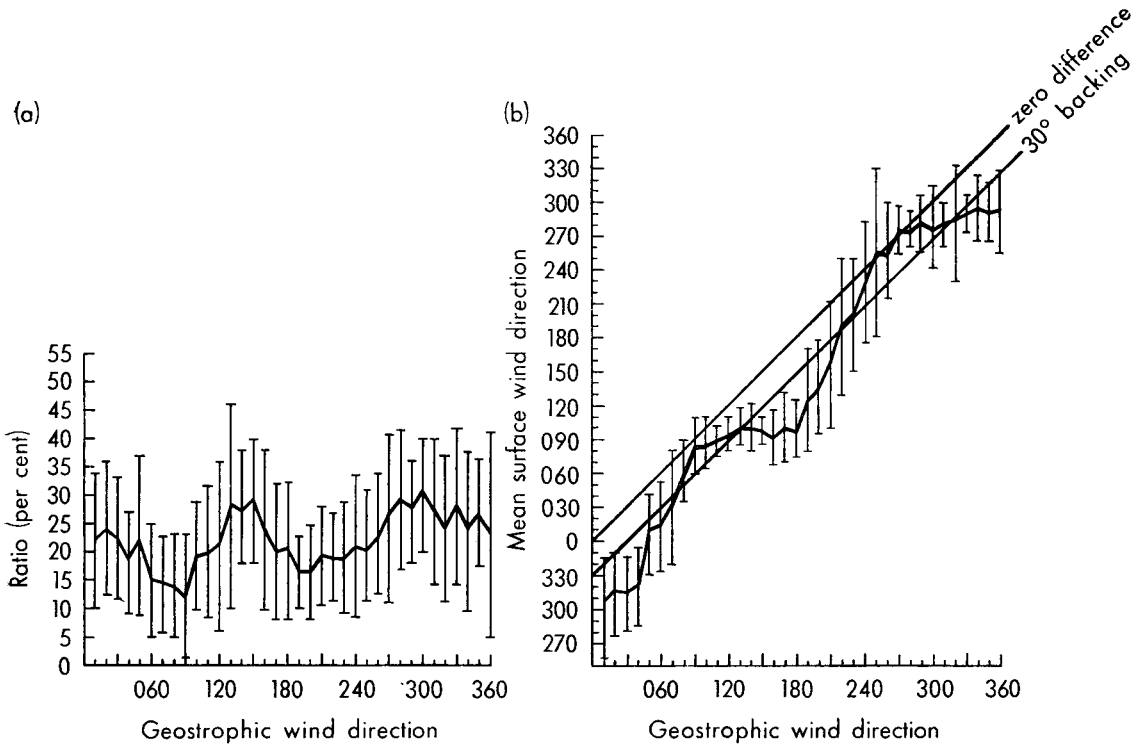

FIGURE 6—TUMMEL

(a) Variation of ratio of surface wind speed to geostrophic wind speed. Vertical lines show standard deviation of ratio.

(b) Variation of mean surface wind direction with geostrophic wind direction. Standard deviation shown by vertical lines. Lines of unit slope included to show theoretical variations for constant backings of 0 and 30°.

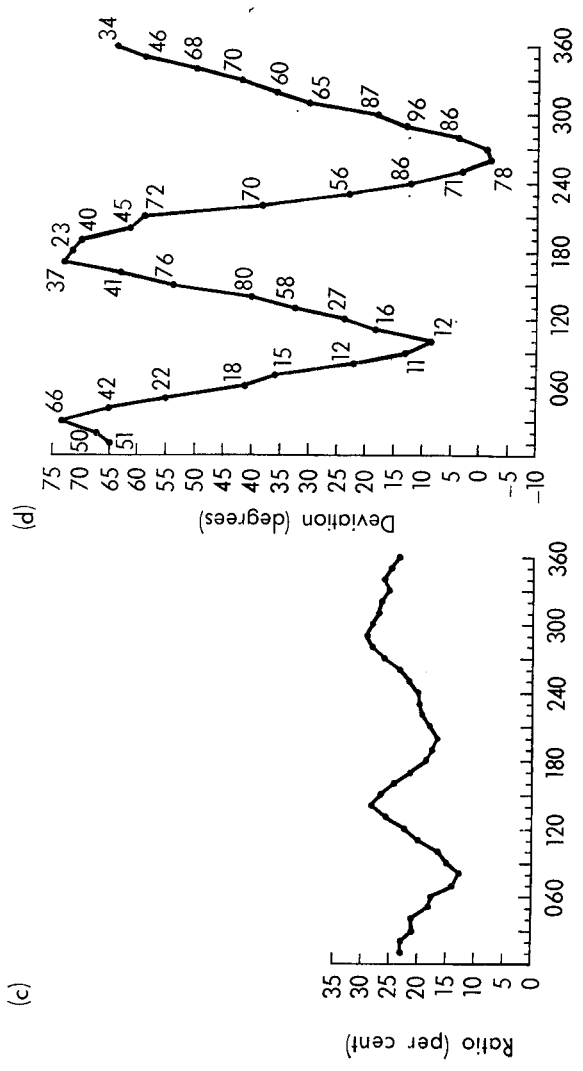

FIGURE 6—*continued*

(c) Variation of ratio of surface wind speed to geostrophic wind speed with geostrophic wind direction; 30° means centred on direction indicated.

(d) Deviation of mean surface wind direction from geostrophic wind direction (from 30° means centred on geostrophic wind direction). Number of samples shown for each direction. Positive values denote backing winds and negative values veering.

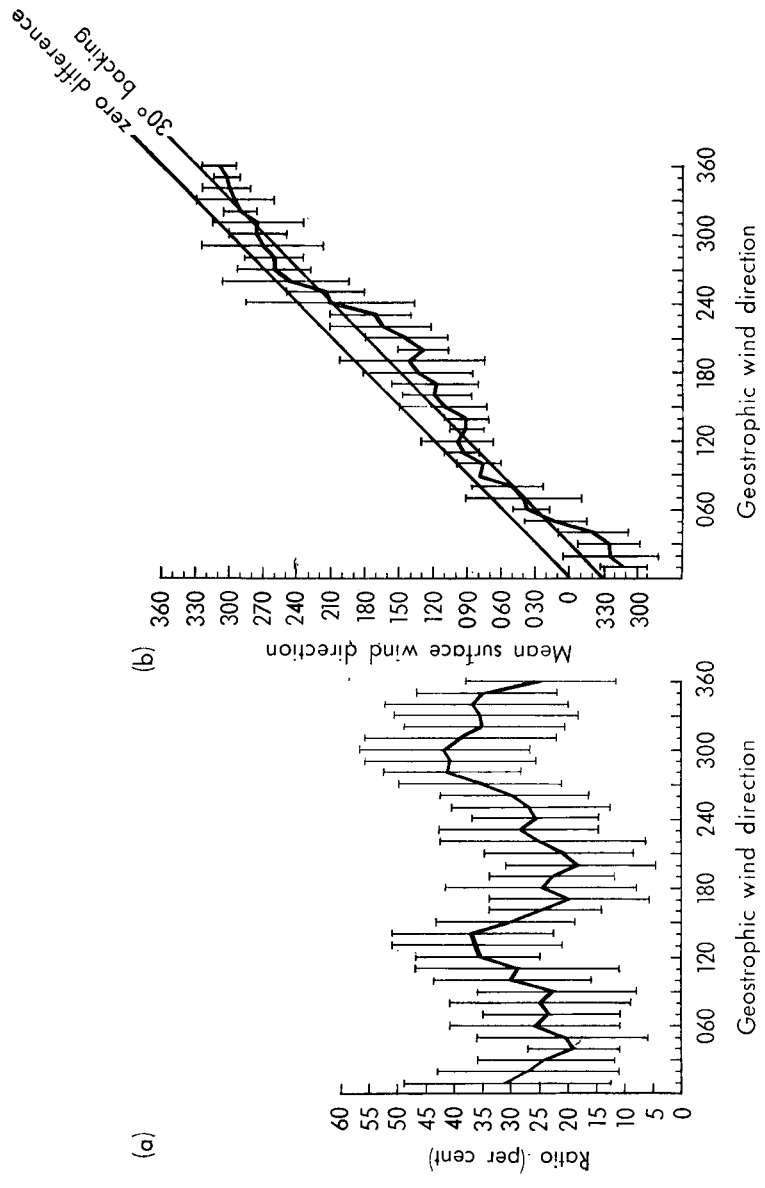

FIGURE 7—SHIN
See notes below Figure 6.

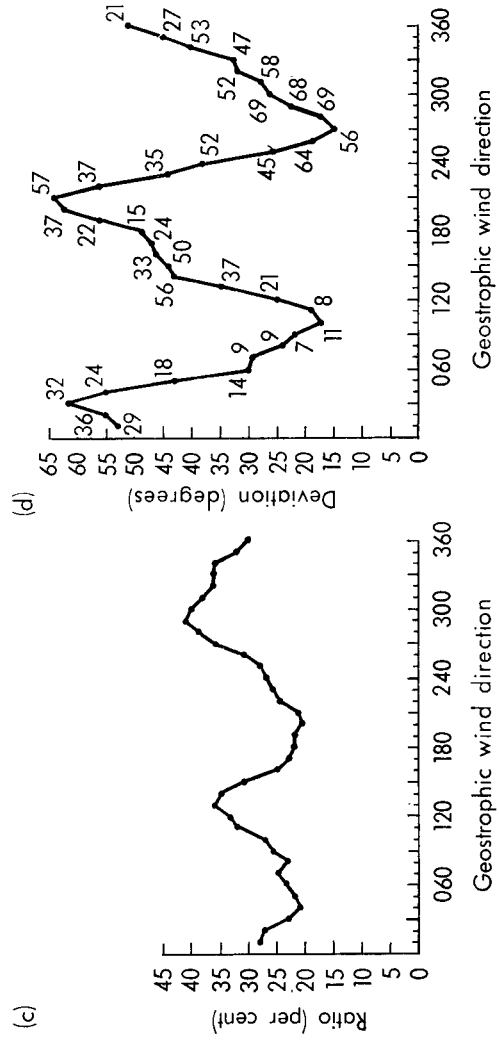

FIGURE 7—*continued*

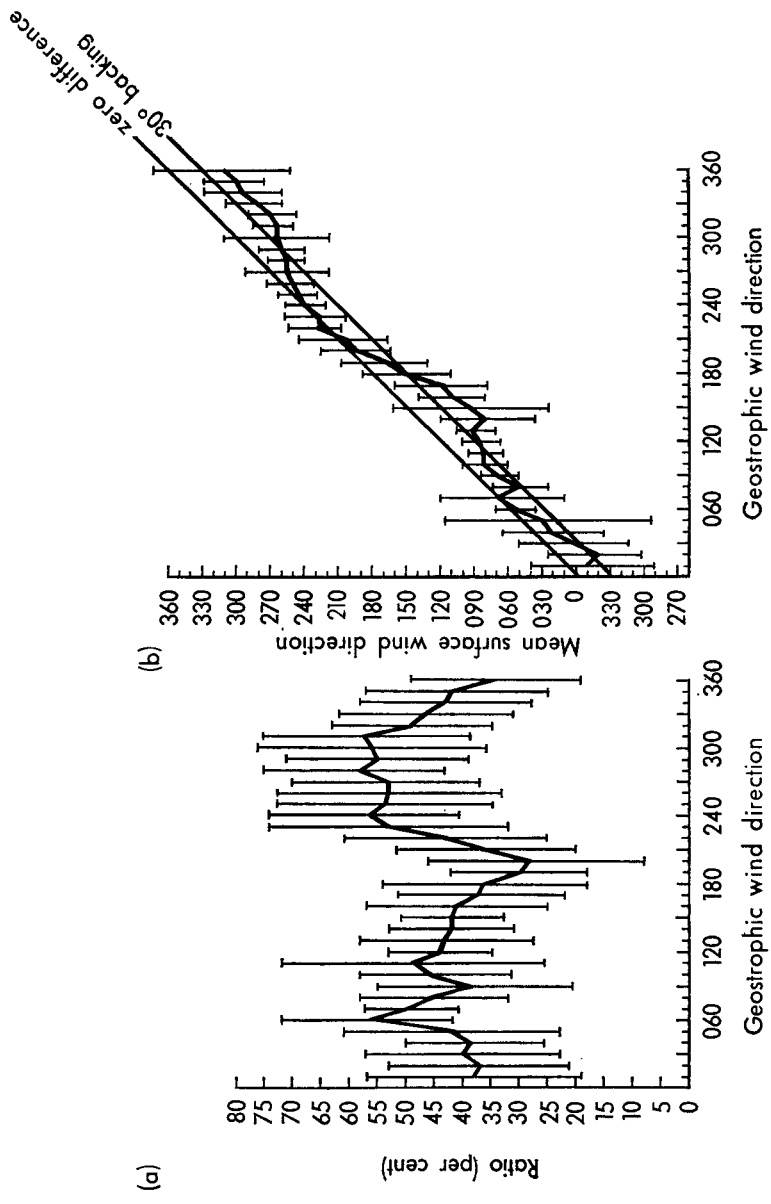

FIGURE 8—RANNOCH
See notes below Figure 6.

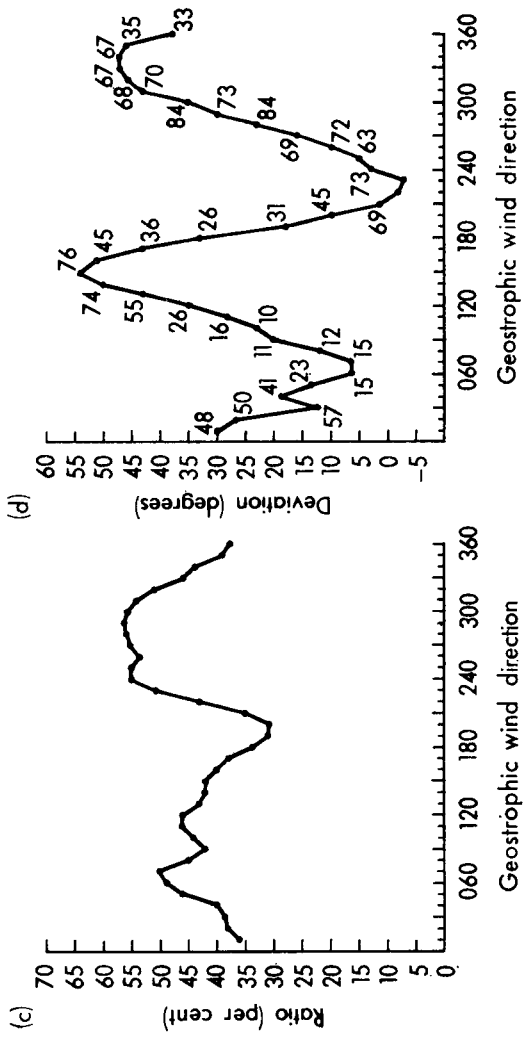

FIGURE 8—*continued*

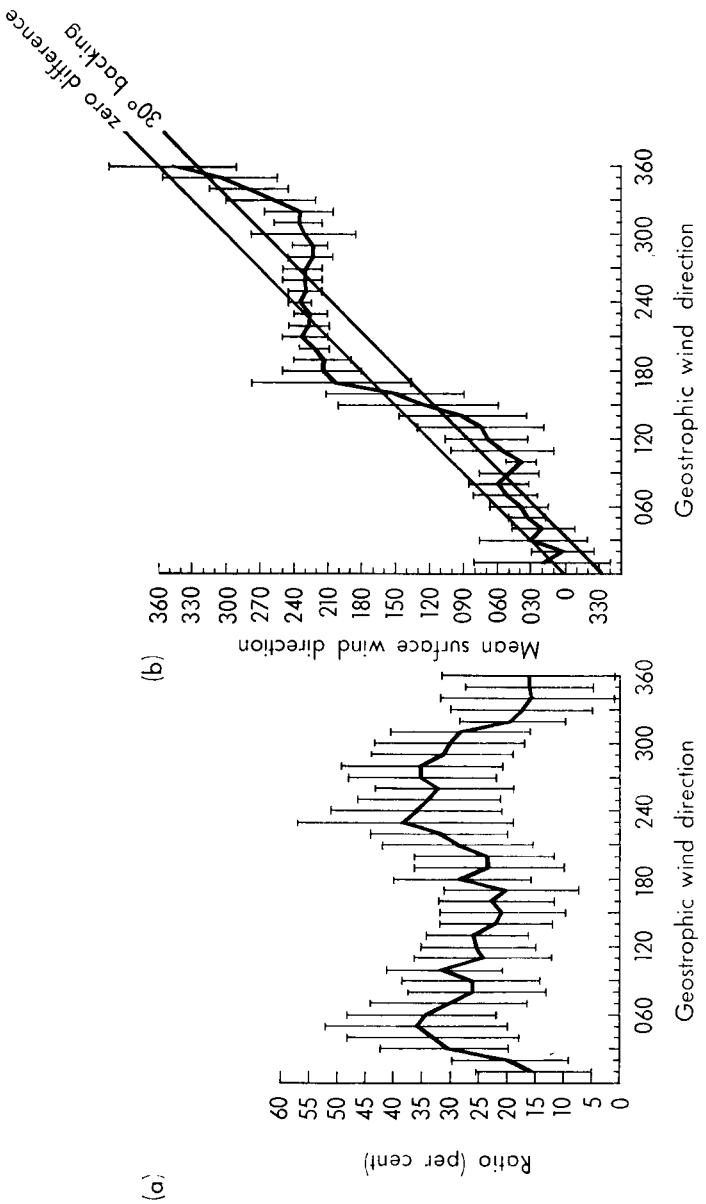

FIGURE 9—FORT AUGUSTUS
See notes below Figure 6.

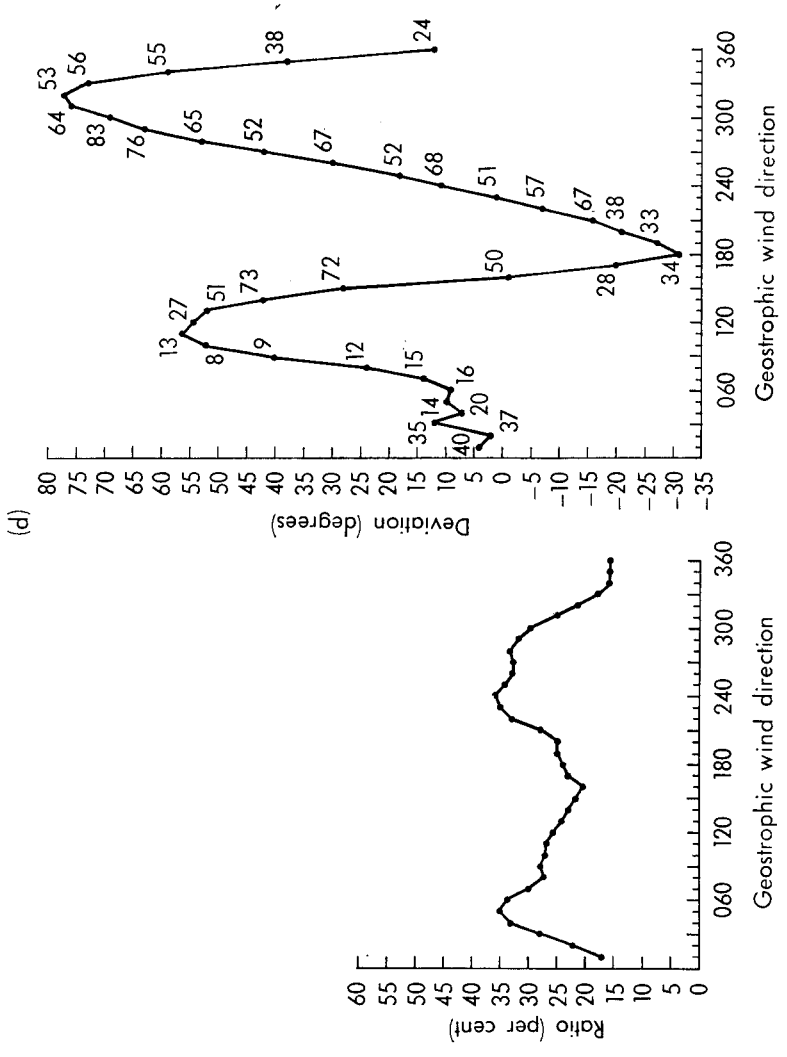

FIGURE 9—*continued*

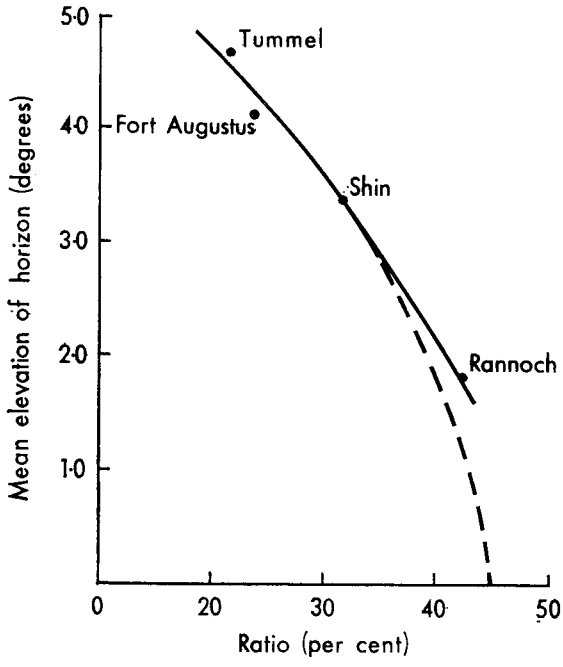

FIGURE 10—MEAN SPEED RATIO FOR ALL WIND DIRECTIONS PLOTTED AGAINST MEAN ELEVATION OF HORIZON FOR ALL FOUR SITES

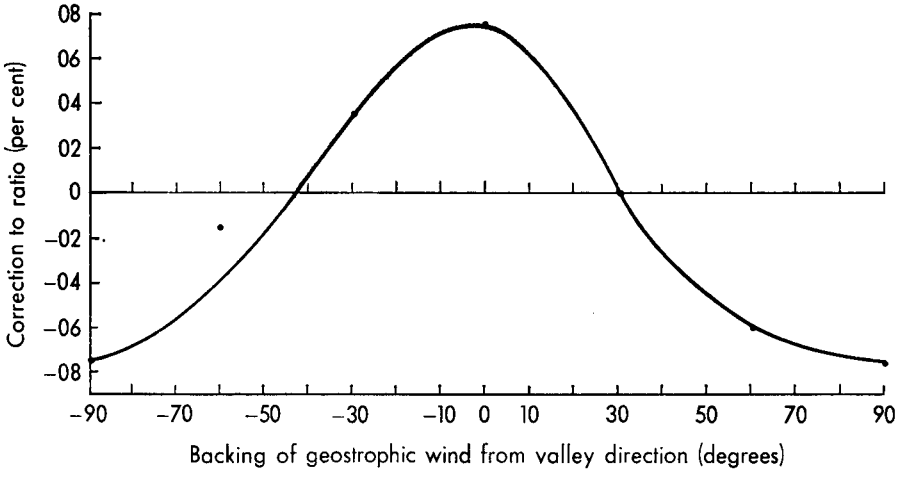

FIGURE 11—CORRECTIONS TO MEAN VALUES OF RATIO OF SURFACE WIND TO GEOSTROPHIC WIND FOR DIFFERENT VALUES OF DIRECTION OF GEOSTROPHIC WIND RELATIVE TO DIRECTION OF VALLEY

influenced by Rannoch which is in an elevated valley nearly 300 m above mean sea level and the dashed line which brings the curve to some value between 0·4 and 0·5 at zero elevation (which of course relates to open, level country) may be more realistic.

The differences between the mean speed ratio and the ratios found for different geostrophic wind directions were determined and the results are plotted in Figure 11. This is a composite diagram including the data from all four sites.

Mean values of the backing of the surface wind from the geostrophic wind were determined for the cross-valley geostrophic wind directions and then at 10° intervals over 180° through the down-valley direction. The results for all four sites are combined in Figure 12.

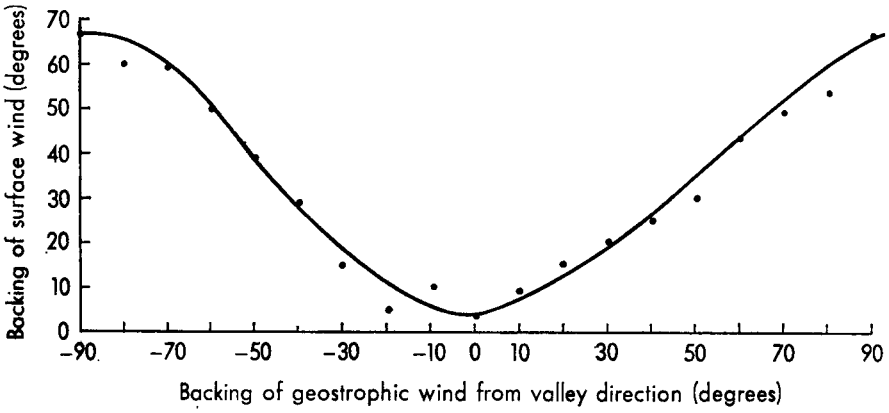

FIGURE 12—BACKING OF SURFACE WIND FROM GEOSTROPHIC WIND FOR DIFFERENT VALUES OF DIRECTION OF GEOSTROPHIC WIND RELATIVE TO DIRECTION OF VALLEY

Figures 10, 11 and 12 enable an estimate to be made of the speed and direction of the wind at an open valley site given the mean elevation of the ground around the site and the geostrophic wind. It should be noted that Figures 6 (a)–9 (a) indicate that the variations of the wind speed are considerable whatever the wind direction with a standard deviation of roughly half the wind speed. As for wind direction, Figures 6 (b)–9 (b) indicate that winds blowing along the valleys tend to be relatively steady but the direction of cross-valley winds fluctuates considerably.

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FORECASTING THE DUCTING OF RADIO WAVES

By M. N. HOUGH
(Main Meteorological Office, Akrotiri, Cyprus)

SUMMARY

Results from atmospheric-refraction theory are used to prepare a diagram which can be used to assess the refractive state of the lower atmosphere from radiosonde ascents. The preparation of radio-wave propagation forecasts are then discussed using this diagram and general meteorological knowledge.

INTRODUCTION

Atmospheric conditions can markedly affect the propagation of radio waves. The refractive index of air varies with pressure, temperature and humidity, and occasionally meteorological conditions lead to unusual propagation (Booker, 1948; Meteorological Office, 1953). Stapley (1964) gave some examples of radar propagation in relation to weather at Gibraltar. Meteorological Offices are sometimes asked to provide forecasts of radio-propagation conditions on a daily basis and this note is an account of the method developed at Episkopi, which uses regularly plotted charts and radiosonde ascents.

METEOROLOGY AND RADIO-WAVE PROPAGATION

The radio refractive index n for air of pressure p mb, temperature T kelvins and specific humidity q g/kg is given by

$$(n - 1).10^6 = \frac{77{\cdot}6}{T} p \left(1 - \frac{q}{4354} + \frac{4800q}{622T}\right) \quad .. \quad .. \quad (1)$$

(Meteorological Office, 1953) where the first constant on the right-hand side has been changed to 77·6 in accordance with Battan (1973). The modified refractive index M is defined by

$$M = (n + \frac{h}{R} - 1).10^6 \quad .. \quad .. \quad .. \quad (2)$$

where h is height above ground level and R is the earth's radius. With this definition the curvature of a radio ray relative to the earth is

$$- 10^{-6} \frac{dM}{dh} \quad .. \quad .. \quad .. \quad .. \quad (3)$$

It has been found convenient to consider ray paths relative to the path in the standard radio atmosphere. This is the international standard atmosphere, but with a constant relative humidity of 80 per cent at all levels. In this standard radio atmosphere M increases with h. If M increases with h less than in this standard radio atmosphere, rays are bent away from the earth less than in the standard atmosphere. This condition is known as super-refraction and implies that the radio horizon is extended beyond the range expected with the standard atmosphere. However, if M increases with h more rapidly than standard, rays are bent away from the earth more than in the standard atmosphere. This condition is known as sub-refraction and is characterized by a radio horizon reduced from the standard.

A special case of super-refraction occurs when M decreases with height. In this case the radio waves are bent towards the earth and may be trapped in a layer known as a duct which results in a very marked extension of the radio horizon. It can be shown (Meteorological Office, 1953) that the condition for radio waves to be bent towards the earth and so form a duct is given by

$$1/(\partial T/\partial h)_{\text{CRIT}}\,\partial T/\partial h + 1/(\partial q/\partial h)_{\text{CRIT}}\,\partial q/\partial h \geqslant 1 \quad . . \quad . . \quad (4)$$

Here $(\partial T/\partial h)_{\text{CRIT}}$ and $(\partial q/\partial h)_{\text{CRIT}}$ are the critical gradients of temperature and humidity respectively. $(\partial T/\partial h)_{\text{CRIT}}$ is the minimum temperature gradient required to satisfy (4) when $\partial q/\partial h = 0$, with a similar definition for $(\partial q/\partial h)_{\text{CRIT}}$. For an atmosphere with $p = 1000$ mb, $T = 288$ kelvins and 80 per cent relative humidity $(\partial T/\partial h)_{\text{CRIT}}$ is $+0{\cdot}087$ kelvins/metre and $(\partial q/\partial h)_{\text{CRIT}}$ is $-0{\cdot}48$ g kg^{-1} (100 ft)$^{-1}$ ($-0{\cdot}016$ g kg^{-1} m^{-1}).

Meteorological situations associated with ducting

Gradients of temperature and humidity similar to or more than the critical values are common and the conditions in which they can be expected to occur can be broadly divided into advection, subsidence and radiation.

Advective situations are typically characterized by warm dry air passing over a colder, wet surface. For example when air from a desert area passes over the sea in summer the air takes up water by evaporation while heat is transferred to the sea from the air which produces a moist layer capped by a temperature inversion. This coincidence of temperature inversion and humidity lapse is very favourable for duct formation since both terms on the left-hand side of expression 4 are additive. The humidity term is often the larger since even an isothermal temperature gradient can reduce turbulence and allow large humidity gradients to build up. Another common advective situation exists in the sea-breeze when cool, moist air over the sea is drawn inland where the air is warmer and drier. The upper surface of the sea-breeze where it meets the land air is a region where suitable humidity and temperature gradients may form.

A different advective situation exists when cold dry air blows over a warmer, wet surface. Evaporation into the dry air produces a steep humidity lapse, so that despite the temperature lapse that is also set up, expression 4 is still satisfied and a duct is formed. Examples include dry Arctic air blowing over the warmer sea, or cold dry air behind a cold front which crosses land that has been wetted by heavy rain.

Subsidence inversions are commonly associated with anticyclones. The air becomes warmer as it subsides while the specific humidity is maintained at the value that existed before descent took place. In this way expression 4 is satisfied but often at a high level above the earth's surface. For radio transmitters near sea level these ducts are usually only important when the subsidence inversion is below about 2000 m while those above 4000 m can normally be ignored.

The formation of a nocturnal surface inversion over land areas when the sky is clear often produces large temperature gradients near the ground. Humidity gradients are usually small so that the temperature term dominates in expression 4. However, if the air is sufficiently moist for fog to form, mixing

occurs within the fog which reduces temperature gradients and the duct is likely to weaken. If the fog has a well-defined top, the hydrolapse may be sufficiently large to cause ducting.

Forecasting ducting conditions

The forecasting method developed at Episkopi makes use of an analysis based on the qualitative ideas mentioned above together with a rough numerical assessment based upon radiosonde ascents and inequality 4. A forecast of future ducting conditions is made using prognostic charts together with any reasonable qualitative changes.

(a) Inequality 4 is represented graphically (Meteorological Office, 1953) and Figure 1 shows this graph with axes suitable for use with tephigrams. The line AB shown as separating an area labelled 'ducting' from one labelled 'partial ducting' is equation 4 with the critical gradients corresponding to the standard radio atmosphere ($T = 15°C, p = 1000$ mb; relative humidity is 80 per cent). Higher in the atmosphere, at say $p = 800$ mb, the critical gradients are 0·8 of their values at 1000 mb, but the temperature is also lower, causing an increase in the critical temperature gradient, but a slight decrease in the critical humidity gradient.

In general then, the line AB should adequately represent most conditions between 1000 and 800 mb, which is the area of most interest in duct forecasting.

The area of 'partial ducting' has been introduced in Figure 1 to allow for inadequacies in radiosonde ascents. Owing to the rate of sampling, the radiosonde averages out much of the steep temperature and humidity gradients that exist. Many tephigrams show isothermal or weak inversion layers which, when plotted in Figure 1, fall above the line AB. Unless it is known with certainty that this is a true representation, it is better to say that ducting will take place in a limited number of directions, or over a restricted area, than to give a definite 'no'. The limit of the partial-ducting area is difficult to fix with precision since it depends upon where the sonde actually took the measurements as it ascended. An upper limit can be placed using the standard radio atmosphere since this corresponds to weak super-refraction when steep gradients are less likely to occur. The two extreme cases are also important: near-zero temperature gradient when steep humidity lapses can form, and near-zero humidity lapses when steep temperature gradients form. In the first case the limit is taken to be the standard atmosphere with linear variation either side while for the second the critical gradients are used. No comment need be made on the subjective nature of this area, and it cannot be taken as anything more than a guide until further evidence is available.

(b) The analysis of ducting conditions is obtained by reading temperature gradients (degrees Celsius per millibar) and humidity gradients (gram per kilogram per millibar) from radiosonde ascents in and around the area where forecasts are required. The graph (Figure 1) is then used to determine whether the combination of temperature and humidity gradients will cause ducting, no ducting, or partial ducting.

It is also important to note the height above sea level of inversions, since low-level inversions are more likely to cause ducting than are high-level inversions, whilst those above 4000 m can normally be disregarded unless the radio transmitter is sighted on a high plateau.

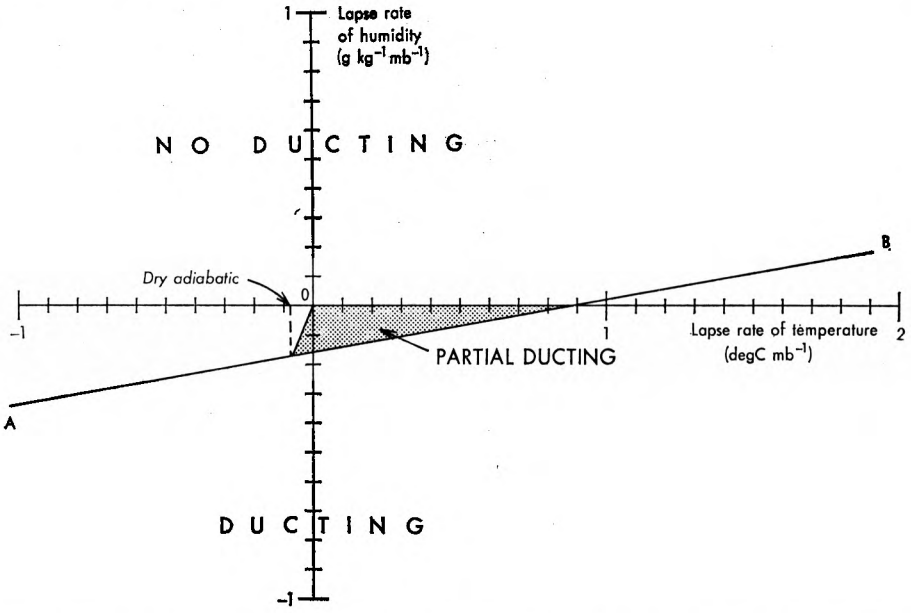

FIGURE I—GRAPH USED TO DETERMINE WHETHER THE ENVIRONMENT MEASURED BY A RADIOSONDE ASCENT WILL CAUSE DUCTING

The line AB separating 'ducting' from 'no ducting' is inequality (4), with the critical gradients corresponding to the standard radio atmosphere. The area of 'partial ducting' is an attempt to allow for the inadequacies of radiosonde ascents (see text). The graph should not be used for pressures below 700 mb.

(c) Forecasts of ducting can then be made using the numerical estimates together with the meteorological ideas stated above. If cloudless weather with light winds is expected during the forecast period then ducting should be forecast in association with the nocturnal surface inversion and the day-time sea-breeze. The only real problems here would be the timing of onset and cessation. Ducting in the sea-breeze occurs soon after the sea air has penetrated inland and then becomes weaker as the circulation dies away in the evening. The onset of ducting with the nocturnal inversion obviously depends upon how quickly the layer of cold air near the ground builds up and ducting will only be important when the steep temperature gradients are above the level of the transmitter. This could be several hours after sunset for tall masts. After dawn ducting will still be present until the inversion has been destroyed by solar heating. Other factors, such as an increase in surface wind, or cloud cover, would also have to be considered if they were to affect the sea-breeze or inversion.

Subsidence inversions below 4000 m are best related to the trough/ridge pattern at 850 and 700 mb. Prognostic charts at these levels are then used to determine the forecast trough or ridge positions and hence to forecast the extent of subsidence inversions. Building ridges or highs are especially important since the height of the subsidence inversion is likely to become lower and cause more marked ducting. When radiosonde data are sparse, some idea

of the lateral extent of subsidence inversions may be obtained by use of the thermal advection pattern at 850 and 700 mb. Marked cold advection implies subsidence and warm advection ascent.

Mountain ranges could complicate forecasts should the requirement be for ducting in a specific direction. A nocturnal surface inversion is normally well below the mountain tops and radio waves trapped in this duct will not go beyond the mountains. Subsidence-inversion ducts may allow propagation over mountains provided that the height of the inversion is above that of the mountains.

Example

Consider the hypothetical 850-mb chart for the eastern Mediterranean in Figure 2 and suppose that a ducting forecast is required at point A, which is

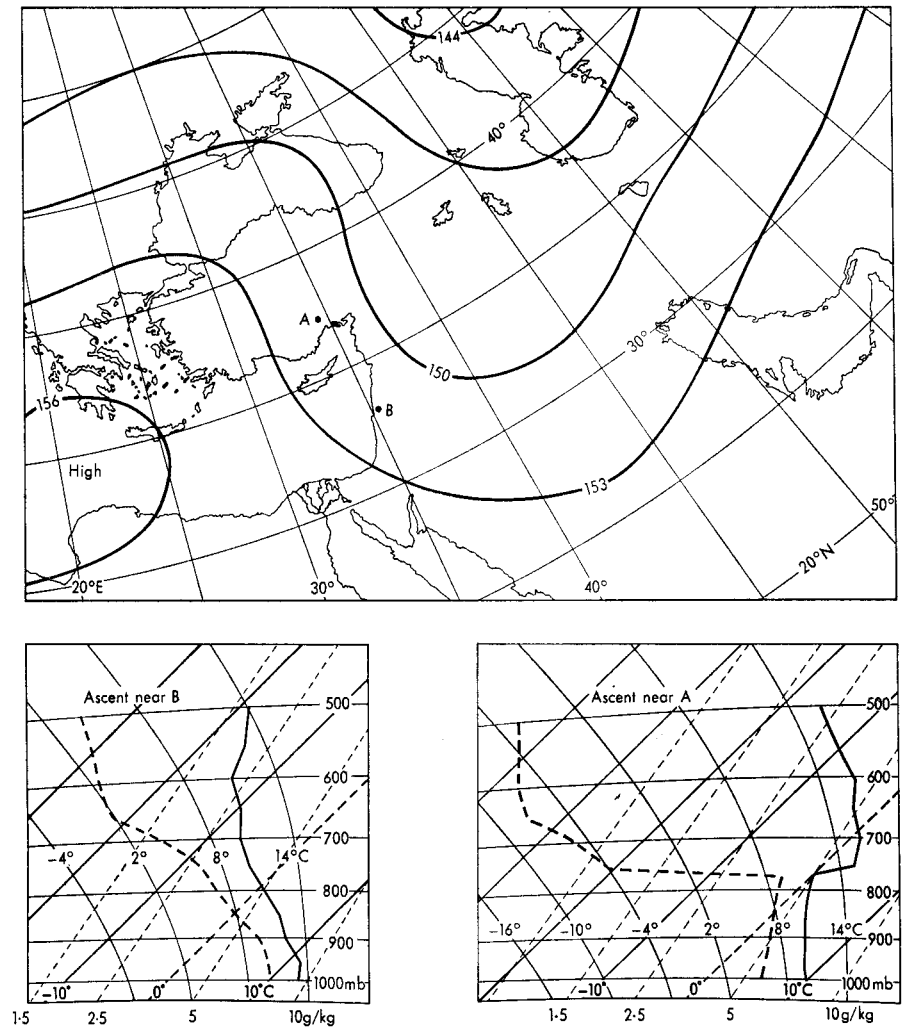

FIGURE 2—HYPOTHETICAL 850-mb CHART FOR 00 GMT ON 22 APRIL

a station 2500 m above mean sea level, and at point B, which is a coastal site, but with mountains rising to 1700 m, 16 km inland.

Representative radiosonde ascents are shown in the ridge and trough.

(1) *Analysis at 00 GMT on 22 April.* Marked subsidence inversion in the ridge over Turkey, but station A is above the level of this inversion. Point B is in the trough, the ascent is unstable and the weather is partly cloudy with showers. Ducting is expected in the ridge, but not in the trough.

(2) *Forecast until 00 GMT on 23 April, issued at 06 GMT on 22 April.* The 850-mb prognostic chart for 12 GMT on 22 April (Figure 3) shows that the trough or ridge system has moved south-eastwards and by that time the subsidence inversion should be starting to affect B. The forecast for B should mention ducting in association with this inversion, beginning at 12 GMT and continuing for the next 12 hours.

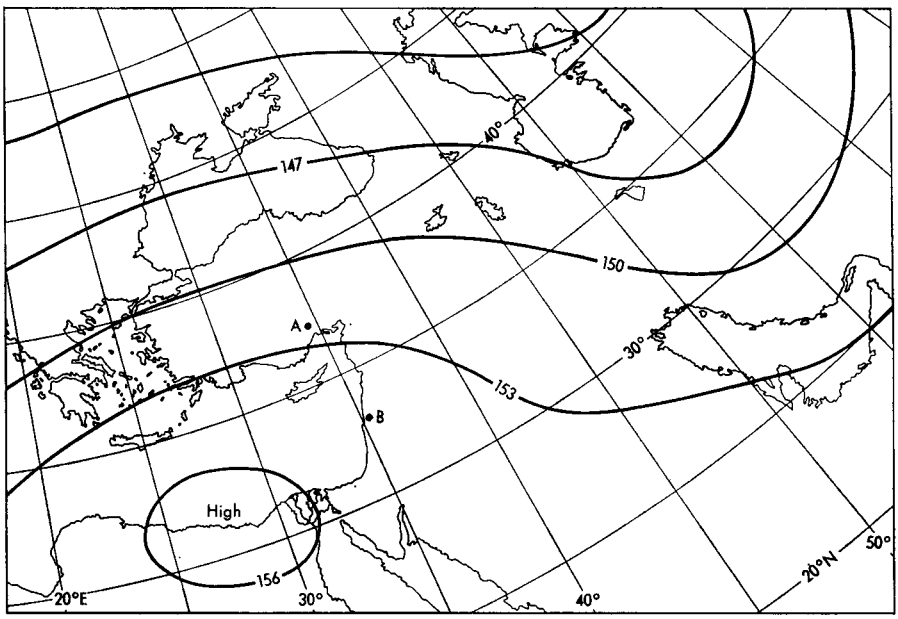

FIGURE 3—HYPOTHETICAL PROGNOSTIC CHART FOR 850 mb FOR 12 GMT ON 22 APRIL

In addition, considerable heating inland is expected during the day in April when the cloud associated with the trough has moved away. The cloud could be expected to delay the onset of a sea-breeze and ducting associated with it should be forecast for the afternoon. Some mention should also be made that the most pronounced ducting will be parallel with the coast, but no more than 16 km inland. No ducting is expected at A during the period. However, if A were in a high-level valley ducting in the nocturnal valley inversion should be mentioned for the last few hours of the forecast period, provided that the sky remains clear and the winds light.

Conclusion

This method could be used by forecasting offices outside the Mediterranean area, since the principles apply anywhere. The full procedure takes about 30 minutes, but a quick assessment could be made from inspection of tephigrams by assuming that all isothermal layers and inversions below 4000 m are associated with ducting.

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REVIEW

Propagation of visible and infrared radiation in the atmosphere, by V. E. Zuev. 240 mm × 160 mm, pp. xii + 405, *illus.*, (translated from the Russian by Israel Program for Scientific Translations, Jerusalem), John Wiley and Sons Ltd, Baffins Lane, Chichester, Sussex, 1974. Price: £13.25.

Professor Zuev's work in the experimental aspects of atmospheric radiative transfer are well known. Recently he has been concerned with the application of radiation theory to the absorption and scattering of laser radiation in the atmosphere, and this comprehensive monograph reflects his research activities and interests. In this way the book serves as a good background for understanding and describing the propagation of laser beams in the atmosphere.

The book consists of three parts. The first part discusses the questions of absorption of visible and infra-red radiation from thermal sources and lasers under various atmospheric conditions. The physical origin of the absorption spectra of atmospheric gases and the analytical description of the absorption are well presented. In this way the discussions are classical. But there is no mention of the basic photochemical reactions of the upper atmosphere. While the abundances of the important minor gases O_3, O_2, CH_4, N_2O, CO etc. are discussed, the possibility of variability of these species is not considered. Neither is there any discussion of the water-vapour dimer model, which we now know to be very important in the continuum absorption in the 8–13-μm region.

The second part of the book presents a study of the aerosol and molecular scattering of visible and infra-red radiation, and thermal sources and optical lasers are considered under different atmospheric conditions. The single scattering characteristics are well covered, but the discussions of multiple scattering by cloud and aerosol particles are poor by present western standards. The Russian school still favours the analytical approach which can treat only the most simplified situations. The numerical techniques for multiple scattering developed during the last decade were available in the literature before the publication of the original Russian edition, and should have been included.

The third part of the book comprises a systematic examination of various aspects of the propagation of radiation beams from lasers and thermal sources in the atmosphere. The basic radiation parameters of different types of laser are considered and the results analysed which concern the structure of the light field in the cross-section of a beam propagating through various scattering media. The effect of turbulent atmospheric motions on the propagation of laser beams is also discussed.

The book suffers in parts from the rapid developments in atmospheric physics since the original Russian book was published in 1970. However, the monograph does contain many tables, figures and a bibliography of 910 entries, primarily Russian, which ideally support the presentation of the theory. The book should therefore be a useful research text to students and research workers in the theory and application of atmospheric radiation transfer.

G. E. HUNT

NOTES AND NEWS

Retirement of Mr E. Evans

On 24 November 1975 Mr Eric Evans retired from the Meteorological Office after a career of 37 years spent largely in the service of the Royal Air Force in a variety of posts at home and overseas.

After studying at the University College of Swansea, where he took the degrees of B.Sc. in 1936 and M.Sc. in 1938, Mr Evans left his native Wales to join the Office as a Technical Officer. Following his training at South Kensington, he went to Wyton as a forecaster. In 1942 he was transferred to High Wycombe as a liaison officer with the United States Army Air Force and was commissioned as Flight Lieutenant in 1943. In 1945 he moved to Transport Command and was detached to Australia for liaison duties as a Squadron Leader.

After demobilization in 1946 Mr Evans was detached as a Senior Scientific Officer to New Zealand for a short time before settling down as a forecaster at Overseas Aircraft Control, Gloucester, for nearly five years. In July 1950 he went overseas again to take charge of the forecasting office at Negombo, Ceylon. From there he moved to Headquarters Near East Air Force at Singapore early in 1952 with promotion to Principal Scientific Officer, and included a short detachment to Iwakuni, Japan, before returning to the United Kingdom at the end of 1953.

The next four years saw him in charge of main meteorological offices, first at Headquarters No. 3 Group, Mildenhall, and then back at Gloucester. His next assignment was to Meteorological Office Headquarers at Victory House where he spent three years in the Defence and International Branch, with special responsibility for NATO affairs. This was followed by a two-and-a-half-year tour of duty back in uniform, this time as a Group Captain at Supreme Headquarters Allied Powers in Europe, Paris.

After his return to the United Kingdom in 1962, Mr Evans spent the next four years at Bracknell as a Senior Forecaster in the Central Forecasting Office. He then went to High Wycombe for nine months as Deputy Chief Meterological Officer at Headquarters Bomber Command before returning to Bracknell for four years in the Defence Services Branch with responsibility for meteorological offices overseas. On 30 December 1970 he was promoted to Senior Principal Scientific Officer and returned to High Wycombe as Chief Meteorological Officer, Headquarters Strike Command. His last posting was back to Bracknell as Assistant Director (Defence Services).

Eric Evans will be remembered for his considerate dealings with staff and a forthright approach to practical problems, to say nothing of his partisan support for Welsh sport. His many friends will wish Eric and his wife a long and happy retirement, with plenty of time to tour the country in their caravan.

M. H. FREEMAN

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It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked 'For Meteorological Magazine'.

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GLOBAL PRESSURE VARIATION AND THE 11-YEAR SOLAR CYCLE

By B. N. PARKER

SUMMARY

Global grid-point pressure data for January and July 1750–1958 were used to investigate possible variations during the 11-year solar cycle. At about latitude 65° in the winter hemisphere a tendency was found for anomaly centres to move eastwards from one annual stage to the next, completing a half-circuit of the globe during one solar cycle. In January the North Sea southerlies were above normal near solar maximum and below near minimum.

Charts of mean anomalies near solar maximum and minimum are presented and discussed, also charts of the difference in pressure between solar maximum and minimum. Significance of the variations is established by analysis of variance.

1. INTRODUCTION

Sunspots are relatively dark patches on the sun, emitting less visible light than surrounding areas, but still about 100 times more than the moon at full. They pass slowly across the face of the sun as it rotates and, if they last long enough, return to the same position in about 27 days (the synodic period), creating a transitory 27-day cycle in solar activity. Owing to causes which are still not fully understood the numbers of sunspots also vary very considerably over a period of about 11 years, the focus of much attention in previous work. Earlier in the century there was a spate of papers correlating sunspot numbers with purely local weather variations, but the tendency in recent years has been to investigate possible effects of the general circulation, and in pursuance of this trend this investigation deals with global-circulation anomalies.

2. THE SOLAR DATA

(a) *The basic data*

The index of solar activity used was the unsmoothed monthly mean sunspot number, R, available from 1749 onwards in publications of the Eidgenössische Sternwarte, Zurich (Parker, 1972). Many other indices exist either as refinements of the sunspot number or as measurements of other solar variables, but most of them have a reasonably high correlation with R, while none of them has so long a record and, since it was essential for the largest possible number of cycles to be included, it was felt that R was the only possible choice.

(b) *Classification into annual stages of the solar cycle*

Baur (1964) established new epochs of solar maximum and minimum from 1750 and his reasons for preferring them to epochs obtained by other methods were accepted.

It has been customary in the past to use the method of superimposed epochs in order to compare, or to mean, years in a similar position of different cycles, but if only one base is used for the superposition the variation of the phase lengths between cycles may lead to the comparison of unlike years. To overcome this problem to a certain extent two bases were used here—the month closest to the maximum and the month closest to the minimum, which were designated X and N respectively—and intervening Januarys and Julys were referred to these bases as successive 12-month intervals starting or ending at the time of the closest extremum under the classification $X-2$, $X-1$, X, $X+1$, $X+2$, $X+3$, $X+4$, $N-2$, $N-1$, N, $N+1$, $N+2$, $N+3$, where $X-2$ denotes a month which is between 30 months and 18 months before the next maximum and $N+3$ is 30 to 42 months after a minimum. Thirteen annual stages rather than 11 were used in order to incorporate into the list of classified months most of the years in long cycles which would otherwise have been neglected.

The classification system was to a certain extent subjective, owing to the variable length of the cycles, in that while most years could have been placed quite definitely in only one stage, there were occasions when in a short cycle a maximum occurred three years after a minimum; in such a case X was used rather than $N+3$. Similarly N rather than $X+4$ was allotted to a minimum falling four years after a maximum. Intervening months were entered under both headings where appropriate. In the longest cycles some months were of necessity omitted altogether. Table I shows which months were used in each annual stage and draws attention to the omission or duplication of dates when this system is used.

The only claim made on behalf of this classification is that it is probably better than one in which merely a single base is used. Other systems which were considered included classifications similarly based on solar maximum and minimum but using fifths of the Wolf number (R) interval between extrema, or otherwise specified absolute values of R as positional criteria. However, it was decided that these latter would not be usable in practice since they would involve forecasting the value of the sunspot maximum up to five years ahead instead of just forecasting its date about two years ahead.

3. The pressure data

These were extracted from the January and July mean pressure charts produced for 1750–1962 by Lamb and Johnson (1966). This source was chosen since it provided the longest available series of homogeneously analysed global charts. The authors' caution regarding the validity of single values was noted, but it was felt that a procedure involving the averaging of anomalies over several cycles would yield more acceptable results on the edges of the analysed areas than the individual years warranted.

The data were available in the magnetic tape data bank of the Synoptic Climatology Branch in the form of grid-point pressure values at intervals of 5° of latitude and 10° of longitude for each January and July from 1750 to 1962. They had undergone comprehensive quality control, but as an additional check

TABLE I—ANNUAL STAGES OF THE SOLAR CYCLE FOR JANUARY AND JULY, CLASSIFIED ON THE BASIS OF THE NUMBER OF YEARS BEFORE OR AFTER THE NEAREST BAUR EXTREMUM.

January

X—2	*X*—1	*X*	*X*+1	*X*+2	*X*+3	*X*+4	*N*—2	*N*—1	*N*	*N*+1	*N*+2	*N*+3
M	M	1750	1751	1752	*1753*	*1754*	*1753*	*1754*	1755	1756	1757	1758
1759	1760	1761	1762	1763	1764	*1765*	*1765*	1766	1767	*1768*	*1769*	M
1768	*1769*	1770	1771	1772	*1773*	*1774*	*1773*	*1774*	1775	*1776*	*1777*	M
1776	*1777*	1778	1779	1780	1781	*1782*	*1782*	1783	1784	1785	*1786*	*1787*
1786	*1787*	1788	1789	1790	1791	1792†	1796	1797	1798	1799	1800	1801†
1803	1804	1805	1806	1807	*1808*	*1809*	*1808*	*1809*	1810	1811	1812	1813
1814	1815	1816	1817	1818	1819	1820	1821	1822	1823	1824	1825	1826†
1828	1829	1830	1831	*1832*	*1833*	M	*1832*	*1833*	1834	*1835*	*1836*	M
1835	*1836*	1837	1838	1839	1840	1841	1842	1843	1844	1845	*1846*	*1847*
1846	*1847*	1848	1849	1850	1851	1852†	1854	1855	1856	1857	*1858*	*1859*
1858	*1859*	1860	1861	1862	1863	1864	1865	1866	1867	*1868*	*1869*	M
1868	*1869*	1870	1871	1872	1873	1874†	1877	1878	1879	1880	1881	*1882*
1882	1883	1884	1885	1886	1887	*1888*	*1888*	1889	1890	1891	*1892*	*1893*
1892	*1893*	1894	1895	1896	1897	1898†	1900	1901	1902	1903	*1904*	*1905*
1904	*1905*	1906	1907	1908	1909	1910	1911	1912	1913	1914	1915	*1916*
1916	1917	1918	1919	1920	*1921*	*1922*	*1921*	*1922*	1923	1924	1925	*1926*
1926	1927	1928	1929	1930	1931	*1932*	*1932*	1933	1934	*1935*	*1936*	M
1935	*1936*	1937	1938	1939	1940	1941	1942	1943	1944	*1945*	*1946*	M
1945	*1946*	1947	1948	1949	1950	1951	1952	1953	1954	1955	*1956*	*1957*
1956	*1957*	1958										

July

X—2	*X*—1	*X*	*X*+1	*X*+2	*X*+3	*X*+4	*N*—2	*N*—1	*N*	*N*+1	*N*+2	*N*+3
M	M	M	1750	1751	1752	*1753*	*1753*	1754	1755	1756	1757	1758
1759	1760	1761	1762	1763	*1764*	*1765*	*1764*	*1765*	1766	*1767*	*1768*	M
1767	*1768*	1769	1770	1771	1772	*1773*	*1773*	1774	1775	*1776*	*1777*	M
1776	*1777*	1778	1779	1780	1781	*1782*	*1782*	1783	1784	*1785*	*1786*	M
1785	*1786*	1787	1788	1789	1790	1791†	1796	1797	1798	1799	1800	1801
1802	1803	1804	1805	1806	1807	*1808*	*1808*	1809	1810	1811	1812	1813
1814	1815	1816	1817	1818	1819	1820	1821	1822	1823	1824	1825	1826
1827	1828	1829	1830	*1831*	*1832*	M	*1831*	*1832*	1833	1834	*1835*	*1836*
1835	*1836*	1837	1838	1839	1840	*1841*	*1841*	1842	1843	1844	*1845*	*1846*
1845	*1846*	1847	1848	1849	1850	1851†	1853	1854	1855	1856	1857	*1858*
1858	1859	1860	1861	1862	1863	1864	1865	1866	1867	*1868*	*1869*	M
1868	*1869*	1870	1871	1872	1873	1874†	1876	1877	1878	1879	1880	1881
1882	1883	1884	1885	1886	*1887*	*1888*	*1887*	*1888*	1889	1890	*1891*	*1892*
1891	*1892*	1893	1894	1895	1896	1897†	1899	1900	1901	1902	1903	*1904*
1904	1905	1906	1907	1908	1909	1910	1911	1912	1913	1914	*1915*	*1916*
1915	*1916*	1917	1918	1919	1920	*1921*	*1921*	1922	1923	1924	1925	*1926*
1926	1927	1928	1929	1930	*1931*	*1932*	*1931*	*1932*	1933	1934	*1935*	*1936*
1935	*1936*	1937	1938	1939	1940	1941	1942	1943	1944	*1945*	*1946*	M
1945	*1946*	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957

Italic figures denote a month which has been repeated in another stage; a dagger (†) shows that some months have been omitted in a long cycle. Where data are missing, or where a month would duplicate an extremum, M is entered.

the charts were printed out and drawn up, and a random selection was compared closely with the original charts. The fact that this process uncovered no significant differences between the two, while not necessarily giving support to an argument that such differences do not exist anywhere in the series, is taken as an indication of above-average reliability of the data, when added to the fact that no marked deviations from smooth isobars were found while the charts were being drawn. Programs were written in the METO language (Craddock, 1966) and run on the Meteorological Office KDF 9 and IBM 360/195 computers.

4. Treatment and results

(a) *Normal charts*

The first process was the computation of January and July normals for the period 1750–1958; these were means of 209 values in the area 25°–70°N, 80°W–30°E, at least 160 values in almost all the area 10°–75°N, 110°W–70°E and at least 114 values in almost all the area 45°S–80°N, 120°W–150°E.

(b) *The annual stages, $X-2$ to $N+3$*

(1) The next processes were the computation of mean charts for each stage and, from these and from the normal charts, the production of anomaly charts for each of the 13 annual stages. Within the area 20°–70°N, 90°W–40°E most of these were based on 18 to 20 cases, but the $N+3$ stage was based on 13 Januarys and 10 Julys (see Table I). Points outside the area stated were covered by fewer years than this.

It had originally been thought unlikely that individual stages would have much in common with adjacent stages, but an examination of the winter hemispheres brought to light a tendency for features in the higher latitudes centred around 65° latitude to move eastwards from one stage to the next. The Hovmöller diagram, at Figure 1 (a), of the change in longitude of January pressure anomalies at 65°N within the mean solar cycle, demonstrates a temporal coherence of spatially associated anomalies that is difficult to ignore; it shows a double-wave structure, each phase of which progresses around half the hemisphere during one solar cycle.

Further verification of the effect is provided by Figure 1(b) which shows that it is also apparent at the same latitude in the southern hemisphere. It should be noted that this diagram is based on many fewer data than is Figure 1(a) and must not be considered to provide more than confirmatory evidence, but it also has a double-wave structure, which tends to be out of phase with that in the northern hemisphere, i.e. at a given longitude and stage the sign of northern-hemisphere anomaly tends to be reversed in the southern hemisphere (287 cases of reversal and 191 of non-reversal). It is difficult to see how two such patterns could have arisen by chance and Figure 1(c) presents, for comparison, the same data as in Figure 1(a) rearranged into random order of annual stages by using a random-number generator on the numbers 1 to 13 to represent $X-2$ to $N+3$. It is fairly obvious that the redistribution has completely destroyed the pattern which was earlier apparent.

(2) Anomalies from the 1750–1958 normal for each annual stage were extracted for points at which the circulation indices are commonly measured. In January there were several details worthy of note and among the most interesting was the oscillation between solar maximum and minimum of the North Sea southerlies. In each of the three stages near maximum ($X-1$, X, $X+1$) the North Sea southerlies, measured as the pressure difference at 55°N between 10°E and 0°, were above normal, while near minimum ($N-1$, N, $N+1$) they were below normal.

(c) *Years grouped in phases*

The initial tendency in this investigation was to concentrate on groups of adjacent annual stages rather than to consider the stage-to-stage variations, since it was originally thought unlikely that the atmosphere actually reacted to

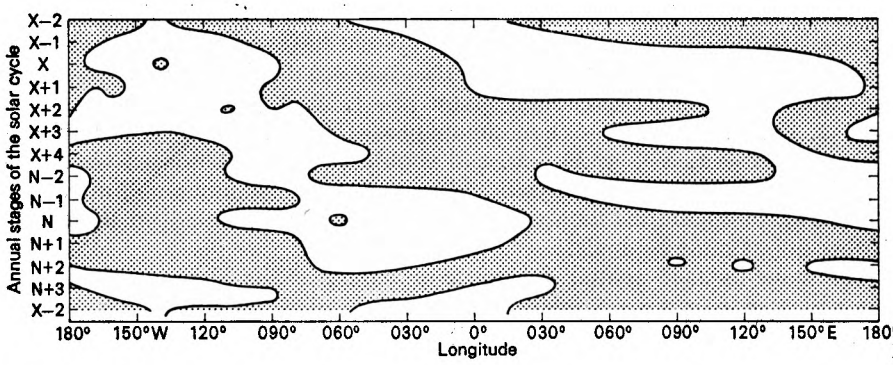

FIGURE 1(a)—CHANGE OF POSITION OF MEAN PRESSURE ANOMALIES FOR JANUARY AT 65°N THROUGH THE SOLAR CYCLE FOR THE PERIOD 1750–1958
Areas of negative anomaly are stippled.

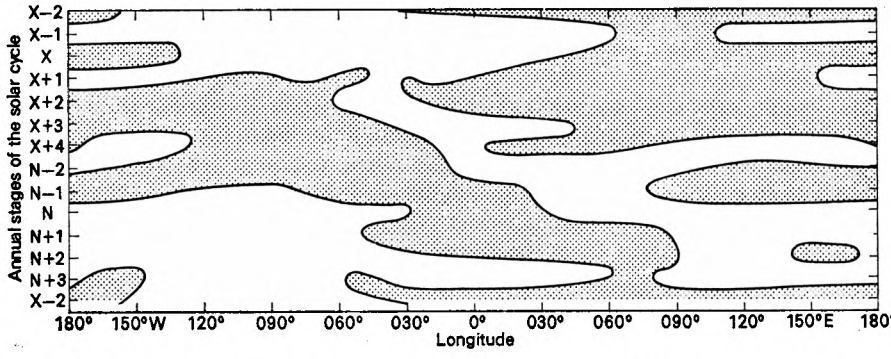

FIGURE 1(b)—CHANGE OF POSITION OF MEAN PRESSURE ANOMALIES FOR JULY AT 65°S THROUGH THE SOLAR CYCLE FOR THE PERIOD 1750–1958
Areas of negative anomaly are stippled.

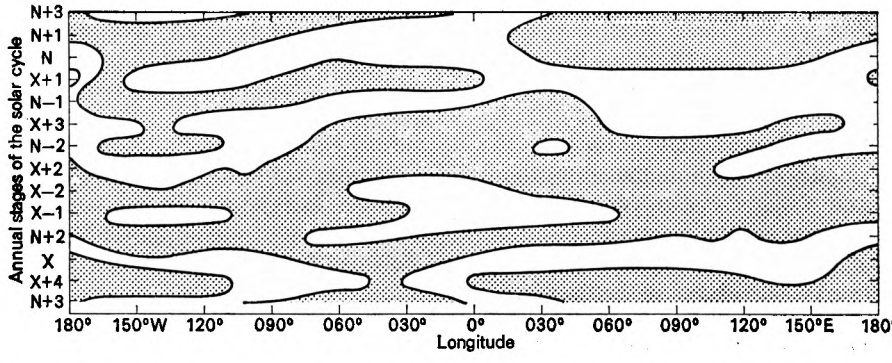

FIGURE 1(c)—CHANGE OF POSITION OF MEAN PRESSURE ANOMALIES FOR JANUARY AT 65°N WHEN THE ANNUAL STAGES OF THE SOLAR CYCLE ARE PUT IN RANDOM ORDER
Areas of negative anomaly are stippled.

the change from $X+2$ to $X+3$ for instance, but possible that it might show an accumulated difference between one set of adjacent stages and another in a totally different part of the cycle. Accordingly the cycle was divided into four phases in the following manner: maximum phase ($X-1$, X, $X+1$), descending phase ($X+2$, $X+3$, $X+4$, $N-2$), minimum phase ($N-1$, N, $N+1$) and ascending phase ($N+2$, $N+3$, $X-2$), and anomalies from the normal were produced for each phase and analysed and those for the maximum and minimum are shown in Figure 2. Lamb (1972) has already commented on these, but further points must be made.

The stage-to-stage spatial coherence of anomalies, as already stated, was much greater than was originally expected, particularly in the middle to high latitudes of the winter hemisphere, but it appeared that the stages of the descending and ascending phases in both January and July were less closely interrelated than those of the maximum and minimum phases, despite the duplication of some years in the ascending and descending phases and the lack of duplication at the extremes. A closer examination of the 'progression' of anomalies in Figures 1(a) and (b) makes this point quite well for 65°N and 65°S in that at the extremes smoother changes of position are evident that in the other two phases.

(1) *January, maximum phase.* The stages on which this chart is based all showed large areas of positive anomaly from Scandinavia to Novaya Zemlya and over the western part of North America, and negative anomalies over almost the entire Atlantic Ocean. Figure 2(a) shows the mean of these to be an accentuation, mainly on the western flank, of all the northern-hemispheric centres of action apart from the Azores anticyclone. This is not true of the southern hemisphere, however, and there seems to be a tendency towards the lows' filling and the highs' declining slightly, with negative anomalies predominating over the oceanic subtropical anticyclone belt, causing a decrease in zonal flow.

(2) *January, minimum phase.* The annual stages each showed zonality in the North Pacific and a slackening of the zonal gradient over the North Atlantic brought about by the filling of the Iceland low. In the southern hemisphere there were indications in all three stages of a deepening or northward movement of the eastern Atlantic lows and a filling or southward movement of the Weddell low.

(3) *July, maximum phase.* In the northern hemisphere each stage showed small positive anomalies along the arctic coast from Scandinavia to Novosibirsk and a slightly stronger negative anomaly over Labrador. In the southern hemisphere the mean of −3 mb south of New Zealand was supported in each stage and the westerlies were slackened between 60°S and Antarctica almost everywhere except in the Pacific.

(4) *July, minimum phase.* The stages all showed cyclonic anomalies over Europe, central Siberia and Alaska, in the Weddell Sea and south of South Africa. Anticyclonic anomalies occurred rather weakly in each stage from the Davis Strait to northern Norway and more strongly south-west of Cape Horn and south of Australia and New Zealand.

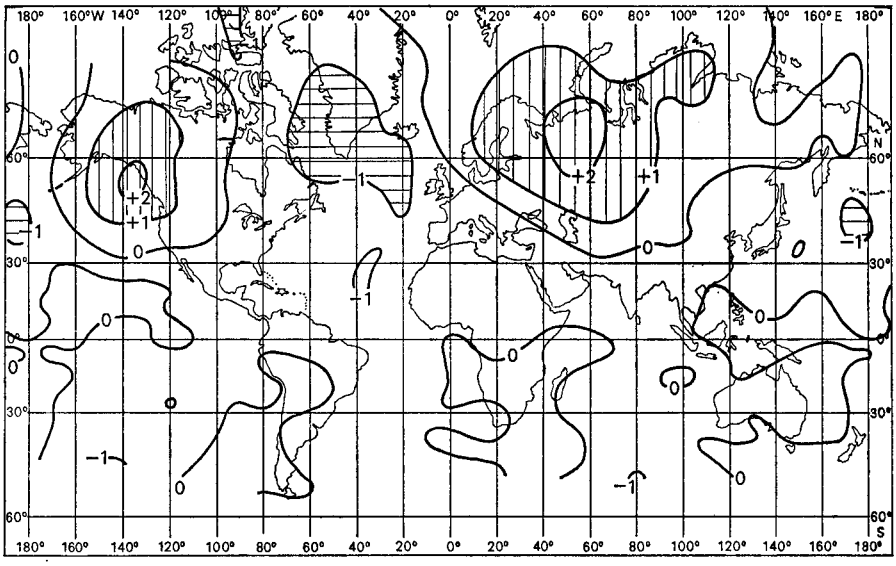

FIGURE 2(a)—PRESSURE ANOMALIES FOR JANUARY, MEANED FOR YEARS NEAR MAXIMA OF THE SOLAR CYCLE $X-1$, X, $X+1$, FOR THE PERIOD 1750–1958

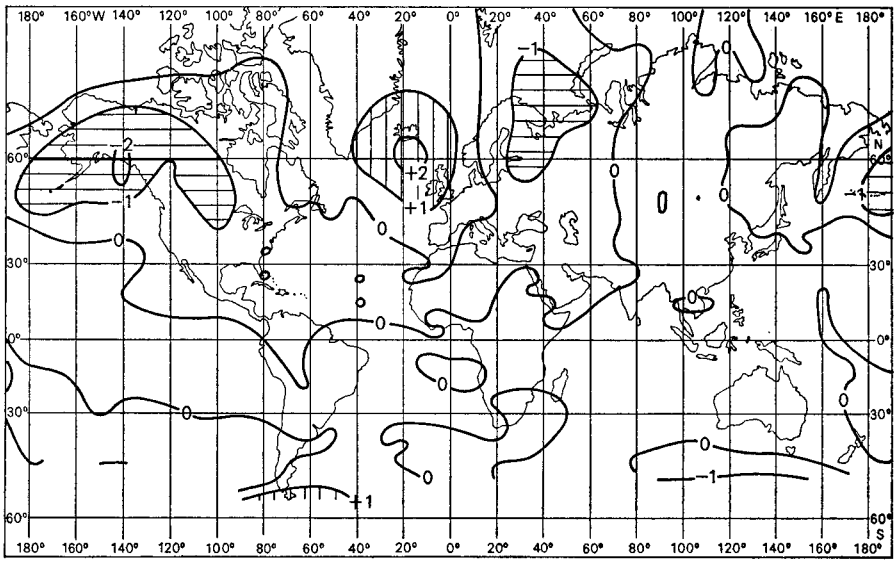

FIGURE 2(b)—PRESSURE ANOMALIES FOR JANUARY, MEANED FOR YEARS NEAR MINIMA OF THE SOLAR CYCLE $N-1$, N, $N+1$, FOR THE PERIOD 1750–1958

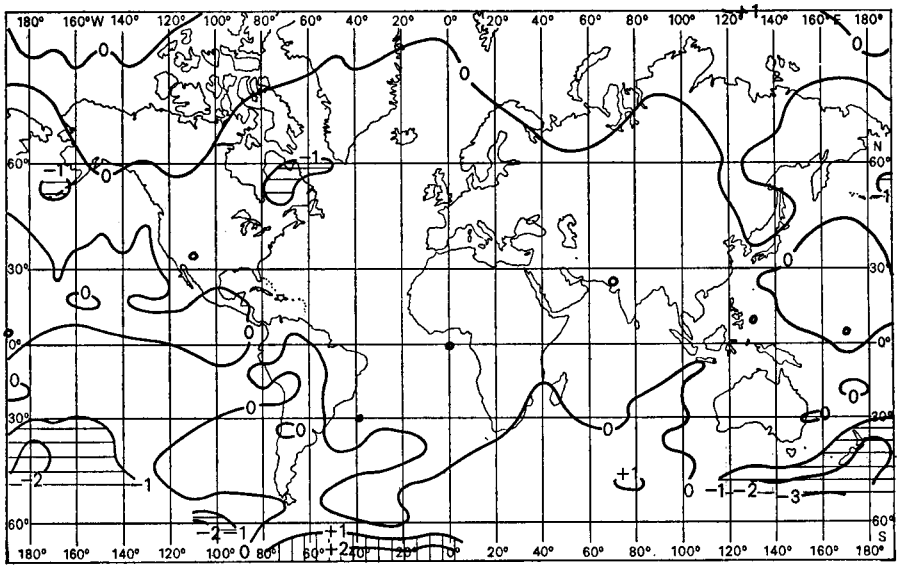

FIGURE 2(c)—PRESSURE ANOMALIES FOR JULY, MEANED FOR YEARS NEAR MAXIMA OF THE SOLAR CYCLE $X-1$, X, $X+1$, FOR THE PERIOD 1750–1958

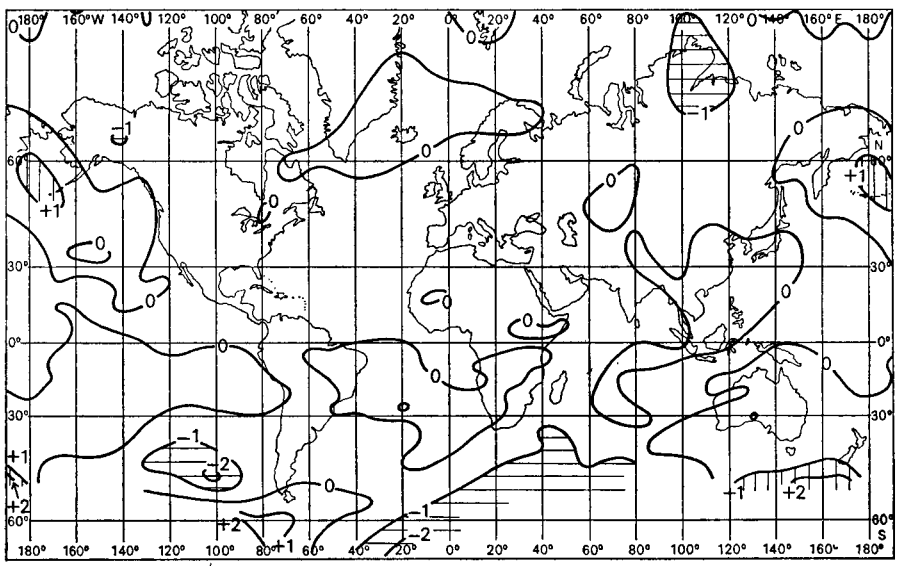

FIGURE 2(d)—PRESSURE ANOMALIES FOR JULY, MEANED FOR YEARS NEAR MINIMA OF THE SOLAR CYCLE $N-1$, N, $N+1$, FOR THE PERIOD 1750–1958

(d) *Differences between solar maximum and minimum*

Figure 1(a) also demonstrates a reversal of the sign of the anomaly at a given longitude from the maximum to the minimum phase.

The oscillation between solar maximum and minimum has been noted before by several authors (Pokrovskaya, 1969, discusses some of them) and as a comparison the anomalies meaned at each grid point for $N-1$, N, and $N+1$ were subtracted algebraically from those for $X-1$, X and $X+1$ using the data for 1750–1958.

The only really adequate tool for assessing the significance of these anomalies was an analysis of variance, which was used to compare the between-phase variance with the within-phase variance at each point. There were up to 113 degrees of freedom for the within-phase variance, depending on the position of the grid point, and one degree of freedom for the between-phase variance.

Figure 3 shows the difference between the mean pressure anomalies at solar maximum and minimum and areas significant at or beyond the 5 per cent, 1 per cent and 0·1 per cent levels. In January (Figure 3(a)) important differences are seen in the positive (1 per cent) which lessens the normal troughing into the Gulf of Alaska, the negative (5 per cent) which deepens the Iceland low and the positive (5 per cent) from the Gulf of Finland to the Barents Sea, which helps to cause the tendency over the North Sea towards southerliness near maximum and northerliness near minimum. There are also indications of a weakening of the Indian Ocean and Australian sectors of the subtropical anticyclone belt, but the largest significant area is the negative (1 per cent) centred over the eastern tip of Brazil, causing an eastward extension to the southern plunge of the Intertropical Convergence Zone (ITCZ) over South America in January.

Figure 3(b) shows the difference between the mean pressure anomalies for the solar maximum and minimum phases in July. The values are of course smaller in the northern hemisphere and larger in the southern hemisphere than those for January. The main features are a negative centre over the Aleutians (5 per cent) which strengthens the south-westerlies around the North Pacific anticyclone, positive over northern North America (5 per cent) increasing the north-easterlies over Hudson Bay, extending to an area of 0·1 per cent over Central America which slackens the easterlies over the Caribbean, negative anomalies again over the eastern tip of Brazil (1 per cent) suggesting a southern position of the ITCZ, positive again from east of South Africa to the Weddell Sea (1 per cent) and negative in a south-west to north-east direction across New Zealand (5 per cent).

Neither chart can be used effectively to prove or to disprove the so-called 'Law of accentuation' (Walker, 1915) which states that at solar maximum, pressure rises in areas of high pressure and falls in areas of low pressure, since the zero isopleth frequently runs through the centre of action, but it is perhaps more often true than not in January, particularly in the northern hemisphere.

There are many similarities between the January and July charts, and one's attention is drawn to the fact that the sign of the centres which are strongly marked in January is reversed in July only over New Zealand and south of Australia; all other centres retain the same sign.

ACKNOWLEDGEMENT

The author is indebted to Mr P. Collison for carrying out the analyses of variance.

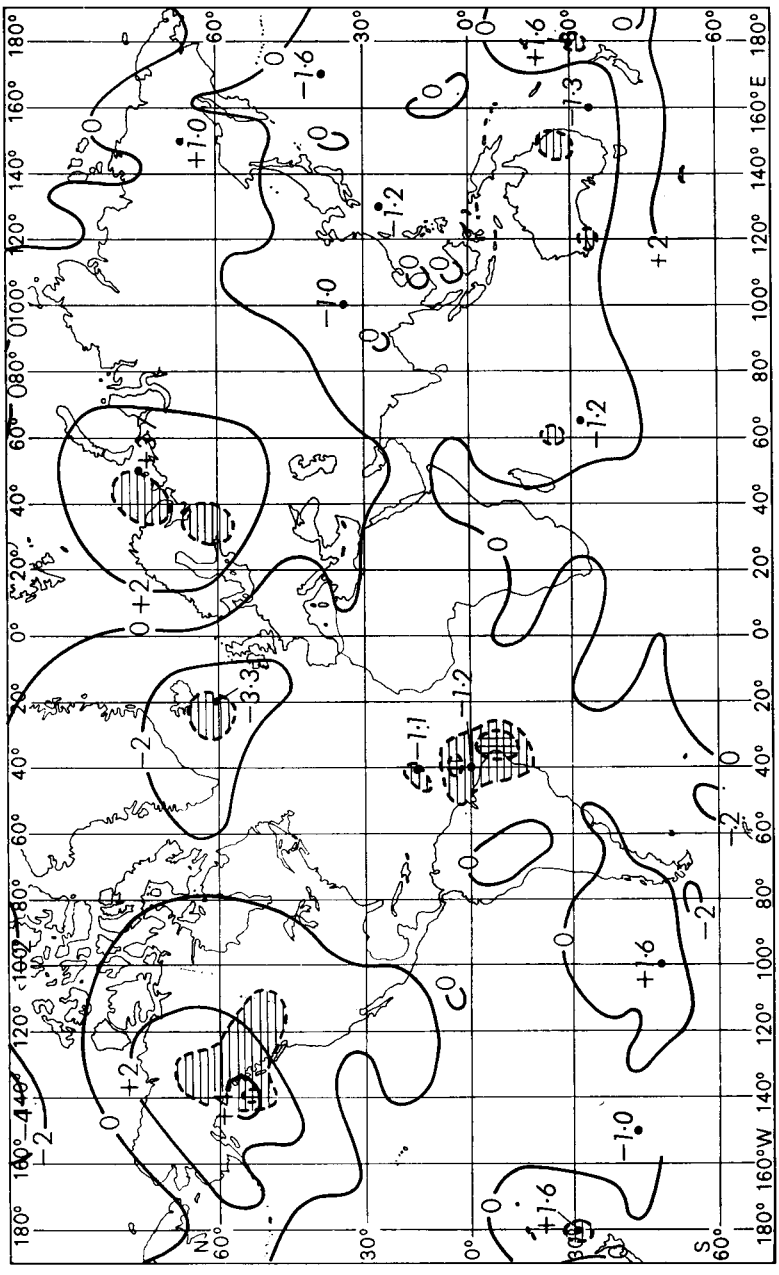

FIGURE 3(a)—DIFFERENCE BETWEEN PRESSURE AT MAXIMUM ($X-1$, X, $X+1$) AND MINIMUM ($N-1$, N, $N+1$) PHASES IN MILLIBARS, AND SIGNIFICANT AREAS BY ANALYSIS OF VARIANCE FOR JANUARYS, 1750–1958

Hatched area significant at 5 per cent or beyond, cross-hatched 1 per cent or beyond.

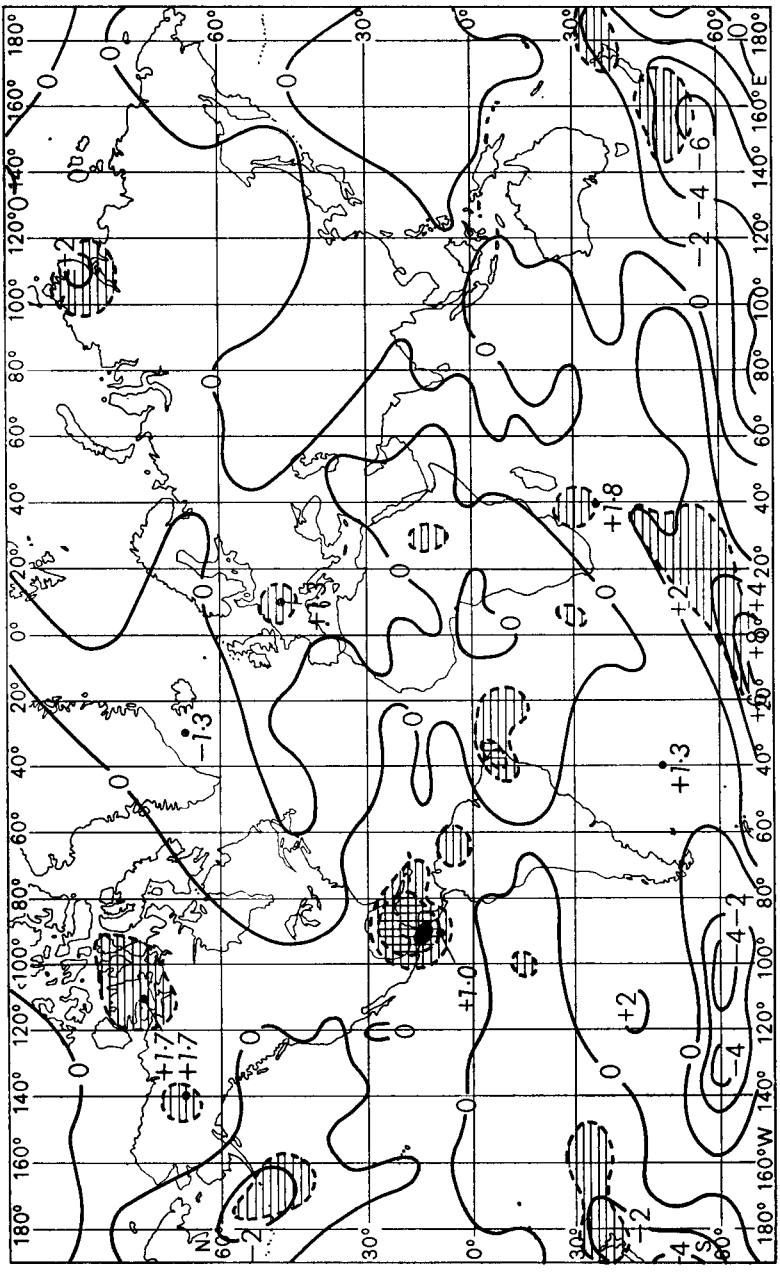

FIGURE 3(b)—DIFFERENCE BETWEEN PRESSURE AT MAXIMUM ($X-1$, X, $X+1$) AND MINIMUM ($N-1$, N, $N+1$) PHASES IN MILLIBARS, AND SIGNIFICANT AREAS BY ANALYSIS OF VARIANCE FOR JULYS, 1750–1958

Hatched area significant at 5 per cent or beyond, cross-hatched 1 per cent or beyond, and solid area 0·1 per cent.

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551.501.771

THE USE OF SURFACE SYNOPTIC DATA TO ESTIMATE UPPER-LEVEL RELATIVE HUMIDITY OVER THE SEA

By P. R. JONAS

SUMMARY

Data from routine radiosonde ascents and surface observations have been analysed to determine the feasibility of using relative humidity estimates derived from surface reports in upper-air analyses where radiosonde data are scarce. It is demonstrated that the errors of the estimates are less than those of a 12-hour forecast used as a background field. The best parameter to use for estimating relative humidity at the standard levels of 850, 700 and 500 mb is the current weather but these estimates can be improved by using additional data such as the cloud type. An example of the effect of estimated data in an objective analysis is presented.

1. INTRODUCTION

The specification of the initial fields of relative humidity, or of water-vapour mixing ratio, for use in numerical models of the atmosphere used for short-range forecasting is a considerable problem in regions where radiosonde data are scarce. Whereas satellite data can provide estimates of the temperature structure in sparse-data regions over the sea, the problem of remote determination of the humidity structure is more complex. At present it is possible to obtain little more than an estimate of the total water content in a column of the atmosphere from satellite observations. In the absence of humidity data, as in the absence of temperature data, the models use a background or first-guess field which can be derived from climatology or from a previous run of the forecast model. However, because of the small-scale structure of humidity fields, the use of these fields can often result in considerable errors in the subsequent analysis.

This note describes a method by which estimates of the relative humidity at 850, 700 and 500 mb can be derived from synoptic surface reports of cloud and weather. The large number of surface reports received from merchant ships can then be used to estimate the upper-level humidity, these estimates being better than the use of a background field. These humidity estimates can be combined with humidity data into an objective analysis and in this note the effect of such data on an analysis is described.

Previous studies of the correlation of surface observations and upper-level humidity have been reported by Chisholm *et alii* (1968). They examined the statistics of dew-point depression using a decision-tree analysis for reliable estimators of upper-level humidity and for less significant cases they derived relations giving the probability of occurrence of various categories of dew-point depression. Since many numerical models use relative humidity as an analysed variable and since this is more readily interpreted in terms of physical processes it was decided to undertake a similar analysis of relative humidity instead of dew-point depression. The significance of an estimate of dew-point depression used by Chisholm *et alii* (1968) was determined by the condition that, at 850 mb, 45 per cent of the cases had dew-point depressions within a 3-deg spread and 60 per cent of cases were within 5 deg. This implies that the results were judged significant if the estimated dew-point was within 2·5 deg of the actual dew-point on 60 per cent of occasions or in terms of relative humidity, that the estimated relative humidity was within about 20 per cent of the actual relative humidity on these occasions. It was hoped that an analysis in terms of relative humidity would improve the accuracy of the estimates. The present analysis was carried out using standard-level humidity data obtained not only from standard-level observations but also from observations which incorporated special points within 50 mb of the standard level. In this way it was hoped that the estimated relative humidities would be more representative of a layer comparable in thickness to those used in many numerical models than those obtained using only standard-level observations. Such a vertical integration should also improve the correlation of the humidity and surface-weather observations.

2. The estimation of humidity

Data have been extracted from the surface and upper-air reports from 7 Atlantic weather stations and 4 island stations shown in Figure 1. The data were extracted over the period 14 August 1973–17 February 1975 and although some of the weather ships were withdrawn during this period all the available reports were included in the analysis since no detectable seasonal variation in humidity estimates was found. The extracted data consisted of the surface report and the mean relative humidity in successive 50-mb layers from 950 mb upwards, obtained using a trapezoidal integration of the standard and special-point temperature and dew-point data. The standard-level humidity data at 850, 700 and 500 mb were then obtained by linear interpolation between adjacent 50-mb layers. Histograms showing the distribution of the relative humidities at the three levels and the number of data analysed are shown in Figure 2.

The aim of this work was to provide estimates of relative humidity which could be derived from merchant-ship reports. These reports seldom contain detailed cloud observations ('8-groups'); because of this and the fact that 00 and 12 GMT observations from moving ships were to be used the estimates of relative

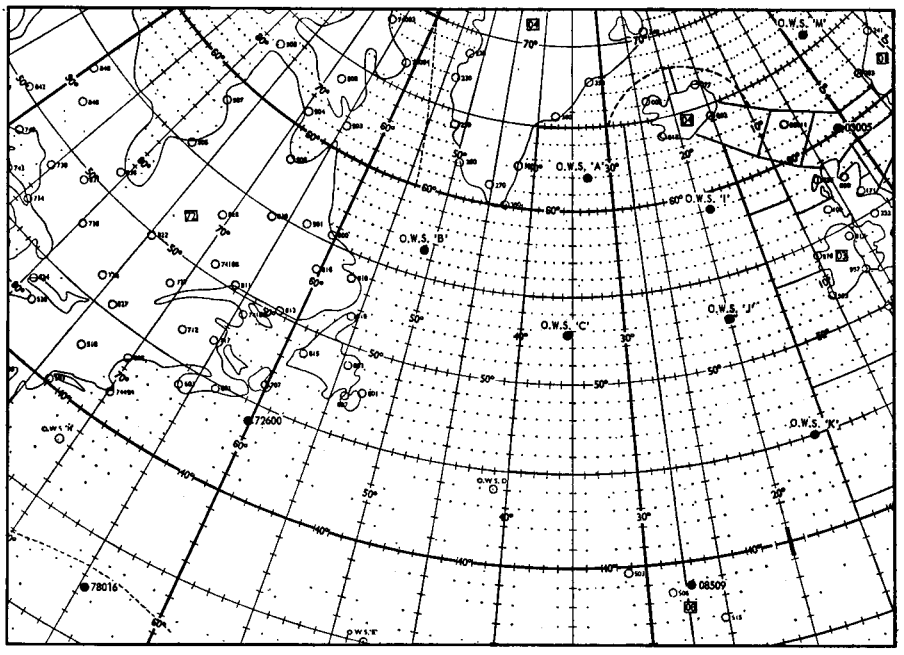


FIGURE 1—LOCATION OF RADIOSONDE STATIONS PROVIDING DATA USED IN THE ANALYSIS OF UPPER-LEVEL RELATIVE HUMIDITY

humidity were based on the reports of current weather (ww) and the standard cloud report ($N_HC_LhC_MC_H$); such estimators as pressure-tendency and past weather were not considered. This restricted analysis has other advantages since it may be possible to obtain estimates of these parameters by interpretation of satellite cloud photographs (Booth, 1973) or of satellite radiance data (Cooley *et alii*, 1970). If this becomes a reliable real-time possibility then the scope of the estimation of humidity could be extended.

There remains the problem of defining a 'reliable estimate of relative humidity'. It is clear that a mean relative humidity could be used but this would be in error on many occasions. Experiments using the Meteorological Office 10-level model (Benwell *et alii*, 1971) suggested that changes in the relative-humidity analysis over a 1000-km square by 10–20 per cent could give rise to significant changes both in 24-hour rainfall forecasts and in pressure forecasts amounting to 8 mb in 24 hours in regions of rapid development. It was hoped therefore that, particularly at the most significant 850-mb level, the estimates of relative humidity would be within about 15 per cent of the observations on the majority of occasions. The estimate of relative humidity derived from a sample of the observations was chosen to be the mid point of the narrowest humidity range containing 70 per cent of the observations. The use of such a median rather than a mean humidity for the estimate reduced the number of occasions when the estimate was in error by more than 15 per cent. Since the use of the estimated data is to reduce the errors in humidity analyses below the level found using the background field it would be desirable to obtain statistics of the differences between humidity background fields and analyses in regions where data exist. Unfortunately such

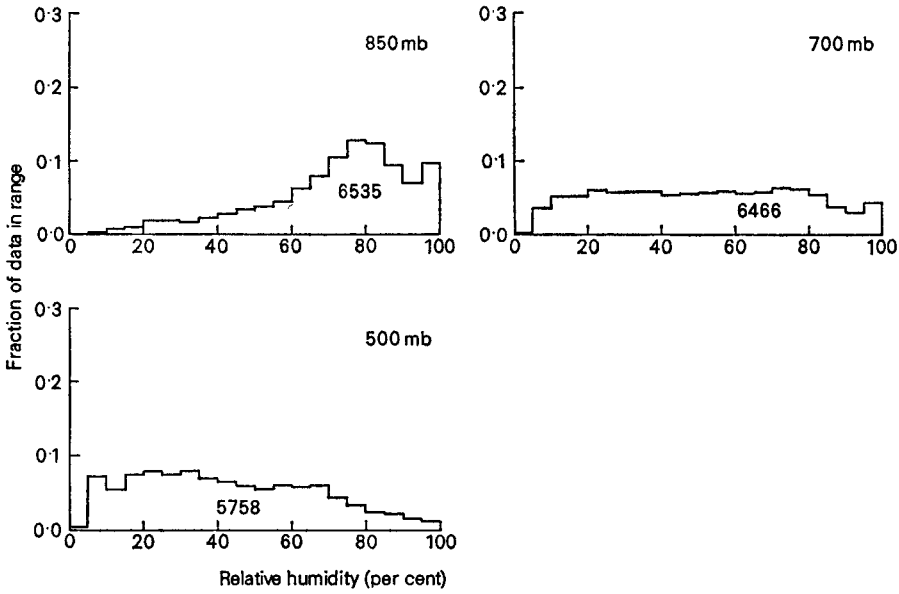


FIGURE 2—HISTOGRAMS SHOWING DISTRIBUTION OF HUMIDITY OBSERVATIONS AT THREE STANDARD LEVELS

data are not available but analysis of the Meteorological Office 12-hour forecasts (an updated 12-hour forecast is used as a background field for this model) suggests that monthly mean humidity errors in the vicinity of the weather ships are about 10 per cent in summer and 15–20 per cent in winter but no figures are available for the root-mean-square errors.

The observations were processed by splitting the sample of data into various categories of present weather and cloud type such that at least 5 per cent fell into each category. A best estimate of the humidity at the standard levels for each category was then obtained. Adjustments were then made to the types included in each category in an attempt to minimize the number of observations of humidity differing from the appropriate estimate by more than 15 per cent.

In the analysis the present weather was split into three categories, dry, showery or wet, the present-weather codes which were assigned to each category being shown in Table I. It was found that at no level was anything to be gained by further subdivision into separate cases of mist or fog (which were included as dry) or of snow or snow showers (included as wet or showery respectively).

At 850 mb it was found that in addition to the present weather the type of low cloud (C_L) was useful. It was found that cases with $C_L = 7$ (indicating bad weather) were best included with the wet cases and cases with $C_L = 3$ or 9 (cumulonimbus) were best included with cases where showers were indicated by the present-weather code. Somewhat surprisingly it was found that the total amount of cloud in the lowest group observed (N_H) was not a useful predictor even if the analysis was restricted to cases where low cloud was present but that the separate classification of very dry cases ($C_L = 0$, no low cloud) did improve the results to a small extent. The best estimates of the 850-mb relative humidities

TABLE I—WEATHER TYPES ASSIGNED TO PRESENT WEATHER CODES

Present-weather code	Weather type
0–12	
28	Dry
30–37	
40–49	
13–19	
25–27	Showery
29	
80–99	
20–24	
38–39	Wet
50–79	

derived from these classes are shown in Table II, histograms of the relative-humidity observations being shown in Figure 3. Using this combination of estimates the fraction of humidity observations differing from the estimated relative humidities by more than 15 per cent was 0·39 and the fraction in error by more than 20 per cent was 0·25. The mean and root-mean-square differences between the estimated and observed relative humidities were 2 and 18 per cent. If an estimate based on the entire data sample had been used only, 56 per cent of the data would have been within 15 per cent of the estimated relative humidity and the mean and root-mean-square differences would have been 11 and 23 per cent.

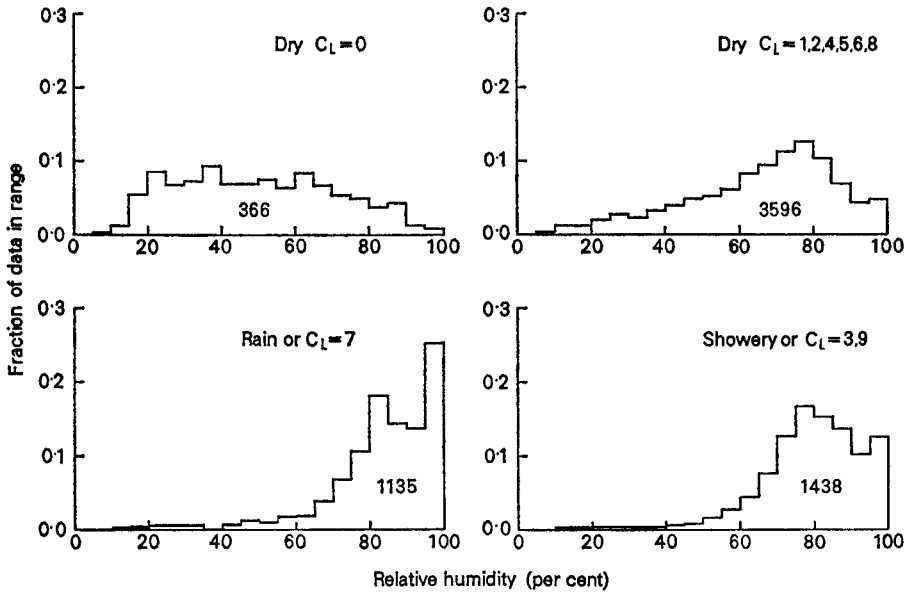


FIGURE 3—HISTOGRAMS SHOWING DISTRIBUTION OF RELATIVE HUMIDITY AT 850 MILLIBARS FOR THE VARIOUS WEATHER TYPES SELECTED TO PROVIDE THE BEST ESTIMATES OF HUMIDITY

TABLE II—ESTIMATES OF RELATIVE HUMIDITY AT 850 MILLIBARS

Weather type and C_L	Number of data	Estimated relative humidity *per cent*	Fraction of data within 15 per cent of estimate
Dry and $C_L = 0$	366	42	0·46
Dry and $C_L = 1,2,4,5,6,8$	3596	66	0·54
Showery or $C_L = 3,9$	1438	79	0·75
Wet or $C_L = 7$	1135	90	0·82

At 700 mb it was also found that the present weather was the main variable to be used in the analysis together with the low and medium cloud types. Reports with $C_L = 7$ or $C_M = 2$ (dense altostratus or nimbostratus) were included with the wet types and again $C_L = 3$ or 9 was taken to imply a showery type. The remaining 'dry' cases were split into three groups: the very dry at middle levels, with a report of no medium-level cloud ($C_M = 0$); the moist, with thicker medium-level cloud ($C_M = 6$, 7, 8 or 9); and the remainder which were included in a separate class. Table III shows the estimates of humidity at 700 mb based on this classification. The mean difference between the estimated and observed relative humidity is 2 per cent, 0·50 of the data are within 15 per cent of the estimate and 0·63 are within 20 per cent.

TABLE III—ESTIMATES OF RELATIVE HUMIDITY AT 700 MILLIBARS

Weather type, C_L and C_M	Number of data	Estimated relative humidity *per cent*	Fraction of data within 15 per cent of estimate
Dry and $C_M = 0$	1772	28	0·51
Dry and $C_M \neq 0,2,6,7,8,9$	594	36	0·36
Dry and $C_M = 6,7,8,9$	355	53	0·29
Showery or $C_L = 3,9$	1197	59	0·45
Wet or $C_L = 7$ or $C_M = 2$	1211	83	0·59

Inspection of Figure 2 shows that the distribution of relative humidity at 500 mb is much more uniform than at lower levels so that the estimated humidities will be less accurate. However, since the mixing ratio is lower at this level than at the other levels, forecasts are less sensitive to errors in the humidity analysis. To obtain a slight improvement in the estimate over a simple mean value, four categories were used. As at the lower levels the classification mainly used the three weather types, observations of $C_M = 2$ being included with the wet cases and $C_L = 3$ or 9 with the showery cases. The dry cases were again split into three groups: very dry, with C_M and $C_H = 0$; moist, with $C_M = 6$, 7, 8 or 9 and $C_H = 2$, 3, 7 or 9; and the remainder. The dry cases with cloud indicating moist conditions at 500 mb were included with the wet cases. The resulting

humidity estimates are shown in Table IV. The mean difference between the estimates and the observed humidities was 4 per cent with 0·52 of the data within 15 per cent of the estimate and 0·65 within 20 per cent.

TABLE IV—ESTIMATES OF RELATIVE HUMIDITY AT 500 MILLIBARS

Weather type, C_L, C_M, C_H	Number of data	Estimated relative humidity *per cent*	Fraction of data within 15 per cent of estimate
Dry and $C_M = 0$ and $C_H = 0$	1157	21	0·63
Dry and $C_M \neq 0,2,6,7,8,9$ or $C_H \neq 2,3,7,9$	2251	28	0·51
Showers and $C_L = 3,9$	1033	39	0·47
Wet and $C_M = 2$ and dry with $C_M = 6,7,8,9$ and $C_H = 2,3,7,9$	1317	60	0·47

These estimates of relative humidity can be incorporated with real data into an analysis scheme and could result in an improvement in the resulting humidity analysis. The next section shows an example in which estimated data have been used to improve a humidity analysis. The method of estimation provides a humidity estimate at 850, 700 and 500 mb from any ship report for which a valid present-weather code is reported. This can sometimes be improved if cloud reports are also obtained.

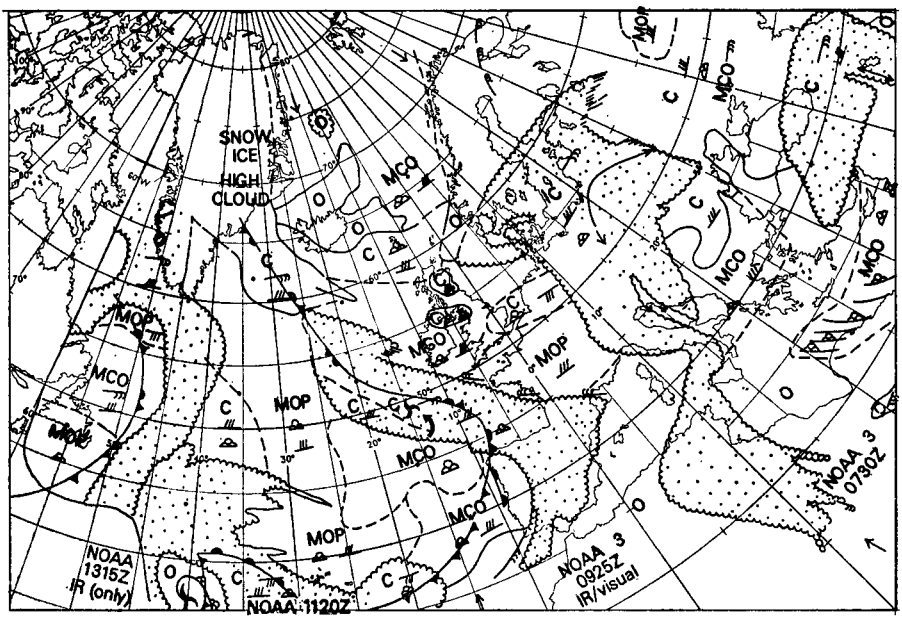


FIGURE 4—NEPHANALYSIS FOR 12 GMT ON 19 NOVEMBER 1974

3. A HUMIDITY ANALYSIS INCLUDING ESTIMATED DATA

The situation chosen for analysis was the chart for 12 GMT on 19 November 1974. The upper-level humidity structure is revealed in the nephanalysis (Figure 4) upon which have been superimposed the surface frontal positions extracted from the *Daily Weather Report* of the Meteorological Office. The main features over the Atlantic are the two bands of cloud associated with the surface fronts between which is an area of broken cloud with extensive convective activity.

The objective humidity-analysis system used for the fine-mesh, limited-area version of the Meteorological Office 10-level model has been described by Atkins (1974). The standard-level humidity observations are interpolated on to surfaces at 100-mb intervals from 350 to 950 mb and the analysis is carried out on these surfaces using a previous forecast field as a background analysis. Asymmetric weighting fields are given to the data to provide, in sparse-data areas, some retention of the shape of features on the background analysis.

The background analyses at 850 mb and 650 mb are shown in Figure 5. Inspection shows that the main frontal system in the eastern Atlantic is present but that behind the front an area of very dry air is apparent. This dry air extends to the southern boundary of the chart, breaking the moist area associated on the nephanalysis with the front in this area. The area of moist air to the east of Newfoundland is shown farther to the west than is indicated by the nephanalysis, resulting in a break in the moist area on the background analysis at about 45°N 47°W which is not obvious from the satellite observations. Therefore although the background analysis contains the general features of the humidity structure there are errors of positioning and intensity of some of the features. The background analyses are probably rather better than average owing to the large amount of subjective intervention which was being included at this date.

The effects of incorporating the radiosonde observations from Atlantic weather ships and land-based stations can be seen in the analyses presented in Figure 6. The main effect on the Atlantic analysis was due to the observations from Ocean Weather Station 'K'. This observation has demonstrated the background analysis error in this area and has raised the humidity at 850 mb from about 20 to 80 per cent which might be expected in a region of convective cloud. The observations from Stations 'I' and 'J' fit in quite well with the background analysis and only minor changes are produced. There are no other changes in the analysis over the North Atlantic because of the absence of data from these regions.

A large number of surface ship observations were obtained on this occasion, most of which, since they contained a valid present-weather code, were capable of yielding upper-level humidity estimates. In order to provide a reasonably uniform coverage of estimated data the area shown in Figure 7 was partitioned into areas of 7·5° of latitude by 7·5° of longitude and a maximum of one estimated observation was obtained for each area. Within the area shown this provides for a maximum of 39 observations which consisted of the first observation retrieved from the data bank for each area. In this case a total of 27 observations were extracted and these are plotted on Figure 7. Conventional notation is used for the plots of ww, C_L, C_M and C_H except that an O is plotted as a cloud symbol if a report of no cloud was obtained to distinguish this from cases of no observation of cloud. These data were used to provide estimates of relative humidity which were included in the analyses shown in Figure 8.

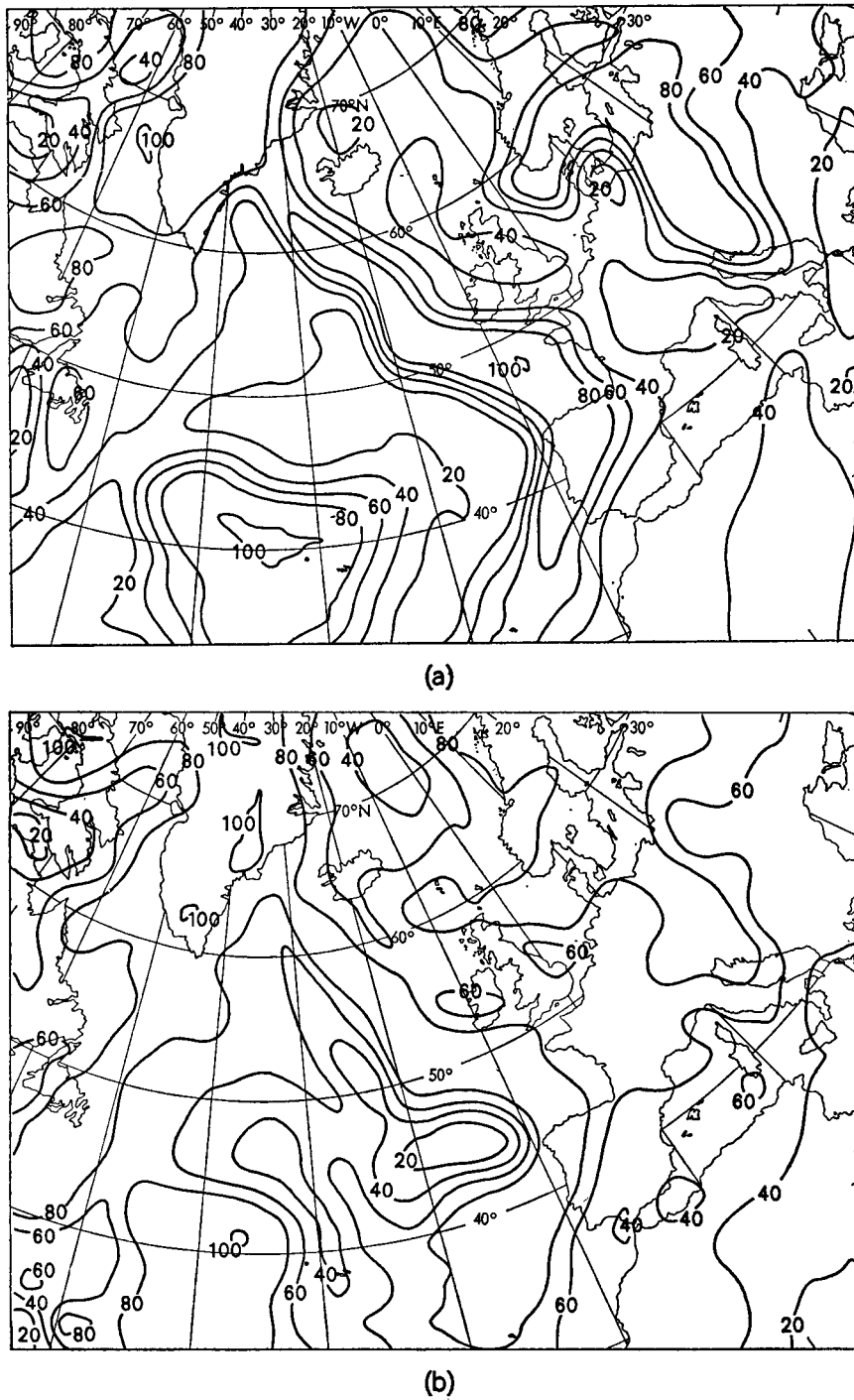
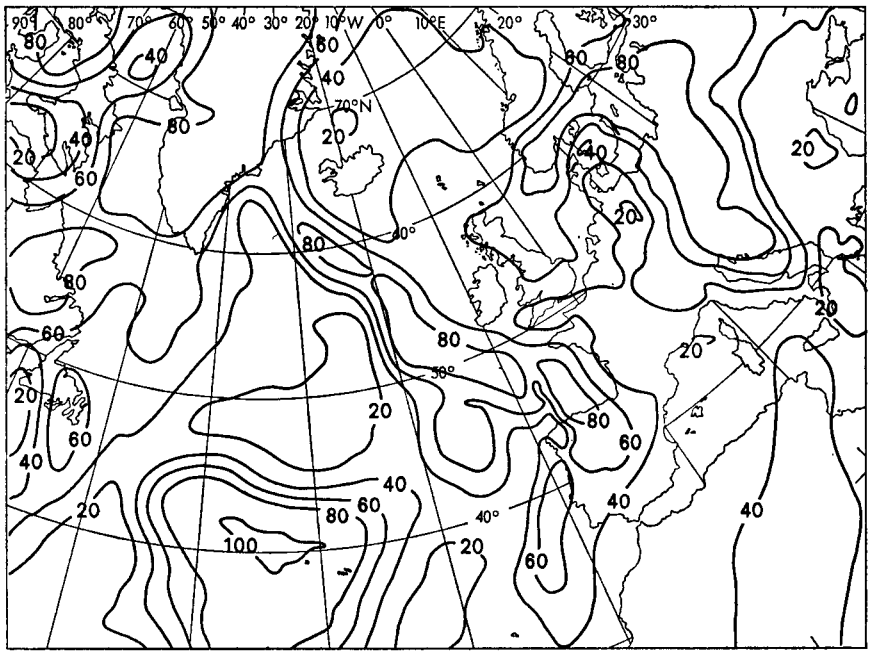
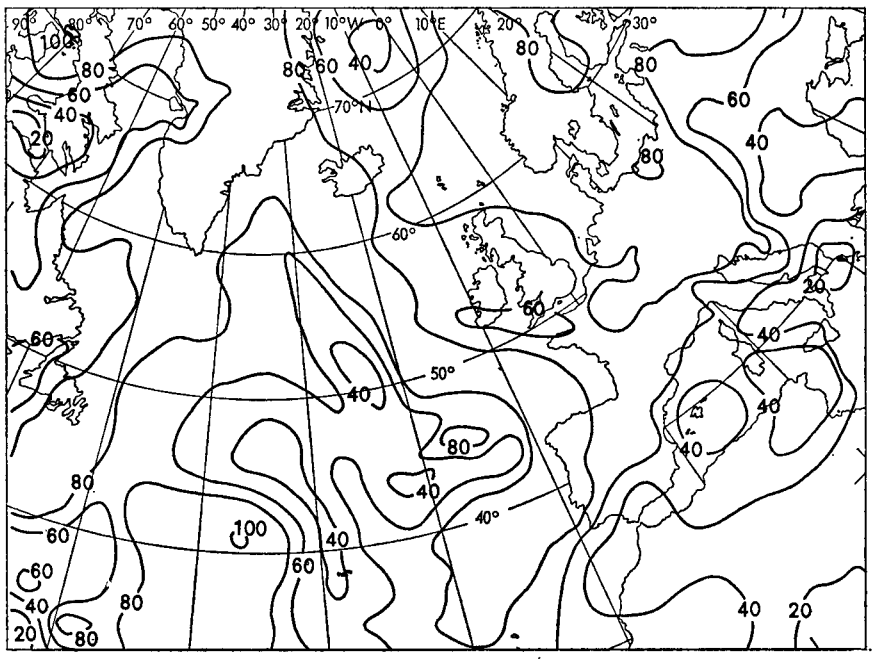


FIGURE 5—BACKGROUND RELATIVE-HUMIDITY ANALYSIS AT (a) 650 AND (b) 850 MILLIBARS FOR 12 GMT ON 19 NOVEMBER 1974



(a)



(b)

FIGURE 6—HUMIDITY ANALYSIS AT (a) 650 AND (b) 850 MILLIBARS FOR 12 GMT ON 19 NOVEMBER 1974 USING CONVENTIONAL RADIOSONDE DATA ONLY

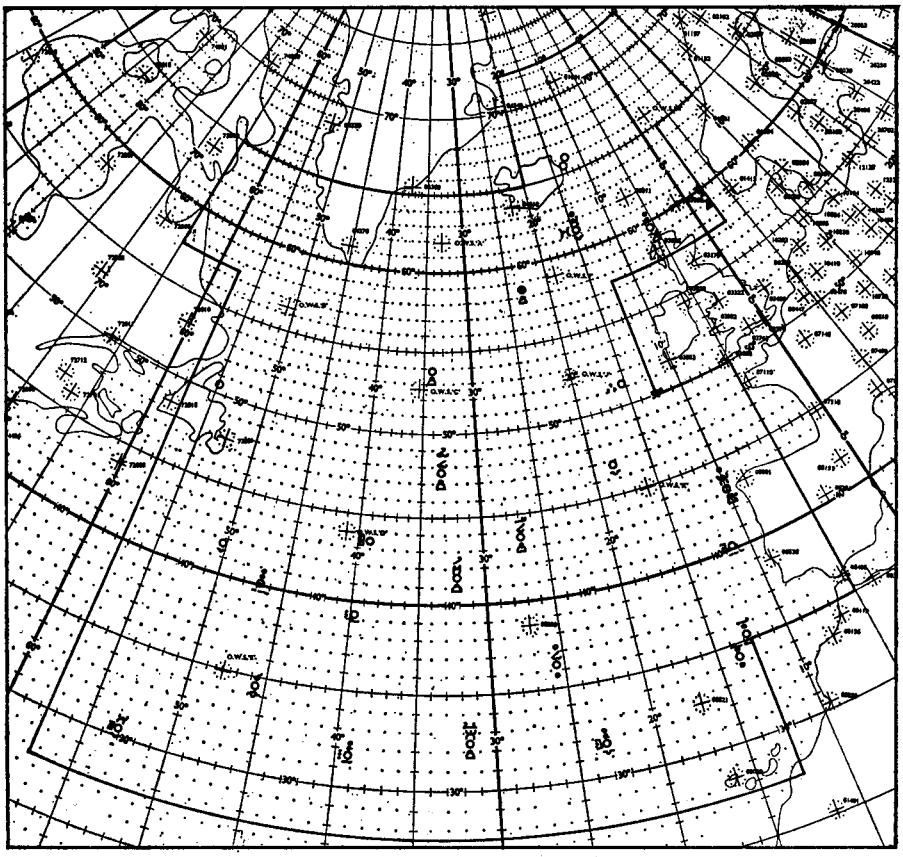
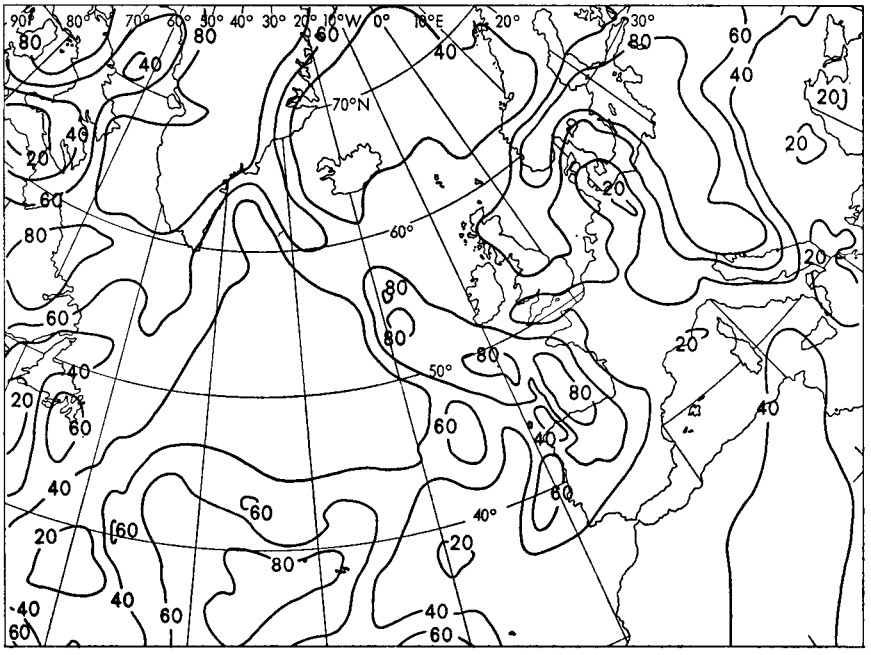


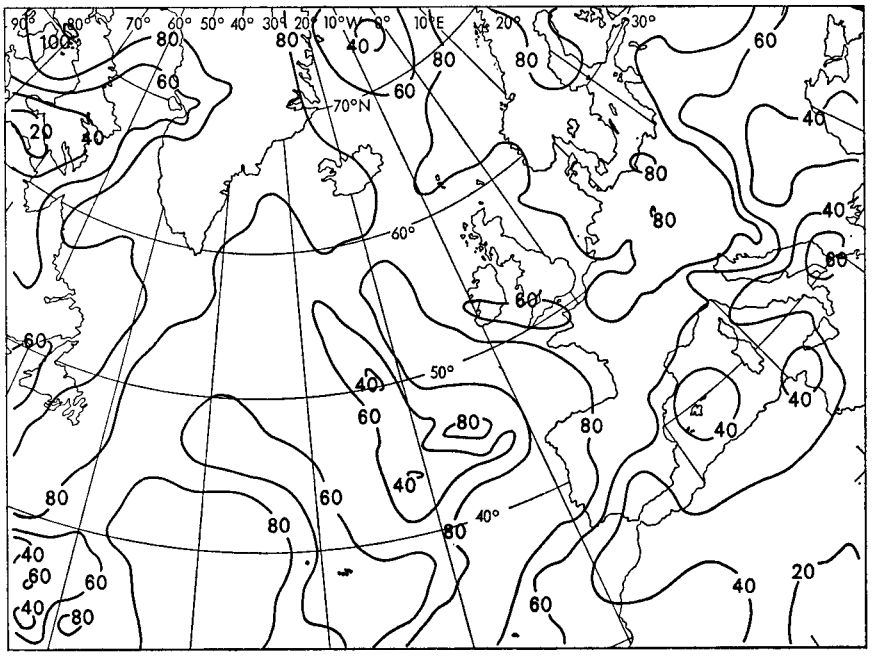
FIGURE 7—LOCATION OF SHIP OBSERVATIONS FOR 12 GMT ON 19 NOVEMBER 1974 USED TO PROVIDE ESTIMATES OF HUMIDITY FROM OBSERVATIONS OF PRESENT WEATHER, AND LOW, MEDIUM, AND HIGH CLOUD TYPE

The boundary of the area from which data were used is shown.

Several differences are apparent between the analyses with conventional data (Figure 7) and those including the estimated humidity data (Figure 8). The major difference is the increase in the humidity to the west of ship 'K'. At both of the levels presented the analysis is closer to that which could be inferred from the nephanalysis which showed convective cloud in this area. The analysis that includes estimated relative humidities has increased the extent of the moist zone near the southern boundary, again consistent with the nephanalysis indication of a belt of cloud linking the main frontal regions. The revised analyses to the south of Iceland are drier than the original analysis would indicate, this also being suggested by the nephanalysis which shows rather less cloud in this area than in the main region of frontal activity farther south. Other minor differences between the analyses include changes at about 40°N 35°W where the effect of the estimated data is to reduce the relative humidities. Although the position of this feature is not changed by the inclusion of estimated data the dry air behind it has been moistened in the revised analysis so that there is slightly less indication of a



(a)



(b)

FIGURE 8—HUMIDITY ANALYSIS AT (a) 650 AND (b) 850 MILLIBARS FOR 12 GMT ON 19 NOVEMBER 1974 INCLUDING ESTIMATED HUMIDITY DATA AT STANDARD LEVELS

break in the region of moist air to the east of Newfoundland than was observed with the conventional analysis. It is unfortunate that there were no observations at about 50°N 45°W which might have improved the analysis at this point.

It can be seen that the effect of including estimated relative humidity data has been to improve the intensity of the analysed features without introducing any serious new errors. The original analysis was comparatively good so that in this case major improvements would not be expected but it can be seen that if the background field had been very bad many of the important features would have been indicated by the use of the estimated data.

4. Conclusions

It has been demonstrated that it is possible to derive useful estimates of upper-level humidity from synoptic surface reports such as those reported by merchant ships. The errors in these estimates are smaller than the errors which might be expected if estimates based on a background field were used. When these estimated data are included in a scheme of objective humidity analysis the effect is to improve the correlation between the analysis and the analysis suggested by the corresponding nephanalysis in areas where conventional radiosonde data are scarce.

Although the coverage of data estimated from merchant-ship surface reports is much better than that of radiosonde observations over the Atlantic there are, as in the example discussed, appreciable areas from which no data can be derived. The analysis carried out in terms of cloud type and weather could be used to provide data derived from satellite cloud photographs if a computer-based scheme for interpreting these in real time could be developed.

Acknowledgement

The author is grateful for the contributions of those members of the Forecasting Research Branch of the Meteorological Office who have been involved at various stages in the progress of this work.

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A NOTE ON THE READINGS OF TWO DIFFERENTLY EXPOSED THERMOMETERS WHEN WATER FREEZES ON CONCRETE

By W. G. RITCHIE

SUMMARY

When free water freezes on concrete, the temperature recorded by a thermometer with its bulb resting on the concrete is about —0·7°C and that recorded by a thermometer embedded so that the bulb is 1·25 cm below the concrete surface is about + 0·4°C.

PURPOSE OF THE EXPERIMENT

It is standard practice in the Meteorological Office to expose at night on a slab of concrete an alcohol-in-glass minimum thermometer, slightly tilted from the horizontal so that the bulb rests on the concrete, and to call the minimum temperature recorded by this thermometer the 'concrete minimum temperature'. This temperature will, however, be affected by the air surrounding the bulb as well as by the concrete surface. It was thought that a thermometer with the bulb embedded just below the concrete surface would also record a temperature near to the concrete surface temperature. This experiment was devised to determine how nearly the temperature of the concrete surface is represented near freezing point by the readings of thermometers exposed in these two ways.

EXPERIMENTAL ARRANGEMENTS

The site of the experiment was the circle of mature concrete 23 m in diameter and from 20 to 30 cm thick in an open site on Wyton airfield which had been used in previous experiments (Ritchie and Virgo, 1973). For another experiment a mercury-in-glass thermometer had been partially embedded in the concrete so that the middle of the bulb was 1·25 cm below the surface (see Figure 1) and the embedding mortar had been coated with a thin layer of waterproof material. An alcohol-in-glass minimum thermometer slightly tilted from the horizontal so that the bulb rested on the surface was exposed near the embedded thermometer. To prevent accidental damage to the thermometers by hares, without materially affecting the exposure of the thermometers to the night sky, a light frame was placed over them. The frame was of angle-strip aluminium, 0·25 cm thick and 1·25 cm wide, in the form of an open 60-cm square with a 30-cm leg at each corner. The base of each leg was inserted into a piece of lead piping 5 cm long to prevent movement by wind. The sides of the frame (but not the top) were covered by wire netting.

FIGURE 1—ILLUSTRATION OF THE POSITION OF AN EMBEDDED THERMOMETER

Stippling denotes mortar.

On nights during the winters 1972/73 and 1973/74 when it seemed likely that there would be frost on the concrete a pint of tap water—freezing point 0°C—was carried from the office and poured on the concrete at sunset at a distance of

about 2 m from the thermometers. The state of this water was noted each time the thermometers were read. If all the water evaporated during the night, another pint was poured. The experiment could be done only on those nights when operations on the station permitted and the thermometers could not be watched continuously, but observed only at hourly or two-hourly intervals as circumstances allowed. The actual temperature recorded by the surface thermometer was noted, not the minimum.

Results

The water froze on 27 nights and these occasions fall into two categories:

(a) On 3 nights the water had partially frozen at the time of an observation and the temperature of the surface was then presumably very near to freezing point. The reading of the surface thermometer was below 0°C on 2 nights and above 0°C on 1 night; the reading of the embedded thermometer was slightly above 0°C on all 3 nights.

(b) On 24 nights the readings of the thermometers when the water froze are not known. On 15 out of the 24 nights the surface thermometer was already recording temperatures below 0°C while the water was still liquid, and on 13 out of the 24 nights the embedded thermometer was still recording temperatures above 0°C after the water had frozen. These facts accord with those of the first category and suggest that when the water was actually freezing, the reading of the surface thermometer was probably slightly below 0°C and that of the embedded thermometer was probably slightly above 0°C.

For the 24 nights when the water froze between observations, estimates of the readings of the thermometers when freezing occurred were first obtained by assuming that on average the reading of each thermometer was then mid way between the readings before and after freezing. Readings of the two thermometers for all 27 nights when freezing occurred (actual observations on 3 nights and estimates for 24 nights) are summarized in Table I.

TABLE I—READINGS OF SURFACE AND EMBEDDED THERMOMETERS WHEN FREEZING OCCURRED

Thermometer	Highest	Lowest	Mean	Standard deviation
		degrees Celsius		
Surface	+0·5	−2·5	−0·7	+0·8
Embedded	+2·3	−0·5	+0·5	+0·6

As an alternative analysis the readings were plotted on arithmetic probability paper (Brooks and Carruthers, 1953). For this purpose the means of the readings for each thermometer before and after freezing were used to determine the rankings (and hence the probabilities) but both readings were plotted for each probability. The idea was to construct on the paper a straight line for each thermometer which intercepted each range between observations made before and after freezing, and thus to determine a description of the data when the water freezes in terms of a mean, a standard deviation, and a normal distribution. It proved possible to construct such straight lines (which failed to intercept only one or two of the observed ranges) and they are shown in Figure 2. This analysis gave means of −0·7°C and +0·4°C with associated standard deviations of 0·7 deg and 0·4 deg for the surface and embedded thermometers

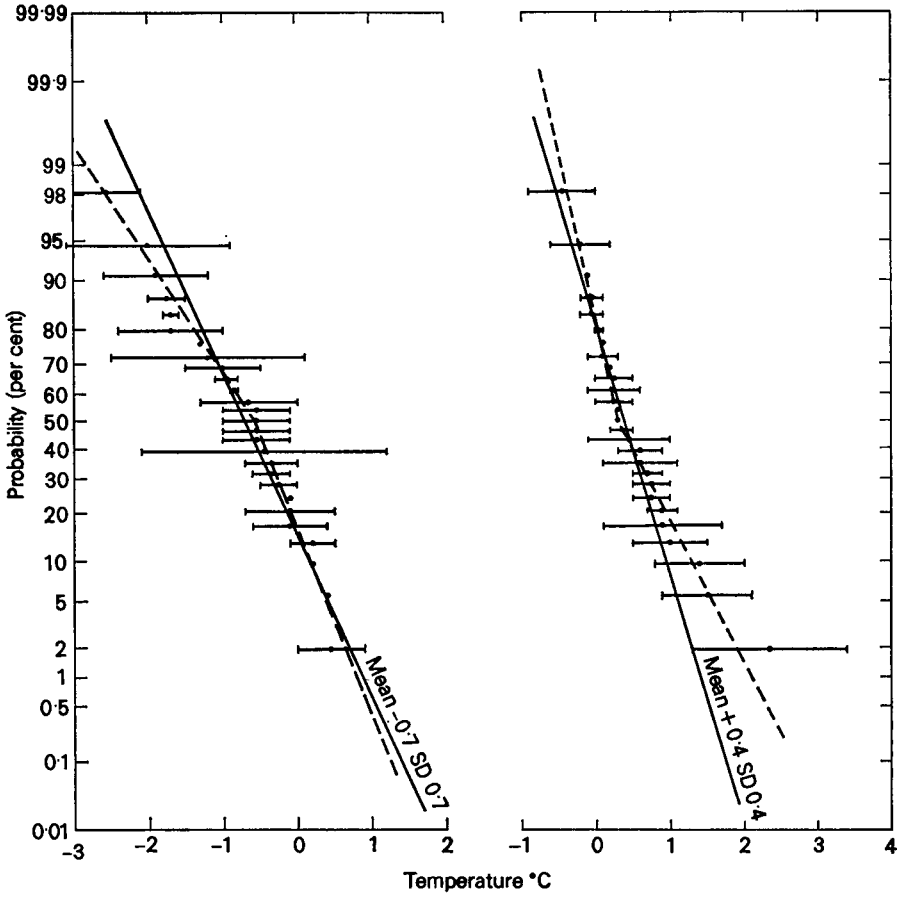

FIGURE 2—ANALYSES OF THE VALUES OF SURFACE THERMOMETER (LEFT) AND EMBEDDED THERMOMETER (RIGHT) PLOTTED ON ARITHMETIC PROBABILITY PAPER

respectively. The analysis also showed that a better fit of the plot of the 'mean' values could be obtained by using two straight lines (shown dashed in Figure 2) joined at the 50 per cent value for each thermometer. These lines kink in opposite directions for the two thermometers, indicating that the distributions of the 'mean' values depart from normal, so that the scatter for the surface thermometer is greater when its indications are more negative than its (negative) average and the scatter for the embedded thermometer is greater when its indications are more positive than its (positive) average.

Further examination of these 'mean' values showed that for each thermometer the departures from 0°C tended to be greater early in the night when the temperature was falling more rapidly than later in the night. Within the limitations of the data the 'mean' values also showed that the surface thermometer indicated 0°C about an hour before the water froze, while the embedded thermometer

indicated 0°C about an hour after the water froze. It is thought likely that the differences in the readings of the thermometers arise because:

(a) The surface thermometer itself radiates and while temperatures are falling cools below the temperature of the concrete surface.

(b) The embedded thermometer is shielded by the surrounding concrete and lags behind the temperature changes of the concrete surface.

For each night on which the water froze the readings of both thermometers before and after freezing were averaged. These averages had a mean of −0·1°C and a standard deviation of 0·4 deg.

Conclusions

When free water freezes on concrete:

(a) The surface thermometer readings are on average about −0·7°C with a standard deviation of 0·7 deg; these readings tend to be more negative early in the night and less negative or even positive later in the night.

(b) The embedded thermometer readings are on average about +0·4°C with a standard deviation of 0·4 deg; these readings tend to be more positive early in the night and less positive later in the night.

(c) The surface thermometer reading falls to 0°C about an hour beforehand and the embedded thermometer reading falls to 0°C about an hour afterwards, on average.

(d) The means of the surface and embedded thermometer readings are on average about −0·1°C with a standard deviation of 0·4 deg.

Acknowledgement

Mr C. L. Hawson suggested this experiment and carried out the analysis on arithmetic probability paper.

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REVIEWS

Everyday meteorology, by A. Austin Miller and M. Parry. 240 mm × 160 mm, pp. 272, *illus.*, Hutchinson & Co (Publishers) Ltd, 3 Fitzroy Square, London, W1, 1975. Price: £4.95.

The first edition of this book was favourably reviewed in the *Meteorological Magazine* for December 1959. In his preface to this, the second edition, the second author claims that the text has been updated and substantially rewritten; it is a pleasure to be able to agree in this instance with a claim all too frequently made about second editions with small justification.

The book is addressed to the interested layman and virtually no mathematics are used. This does lead to difficulties for example in the description of the Coriolis force. In the text this is related to the spin of the earth, whereas what is wanted for horizontal motion is the concept of the component of spin about the local vertical. It was not made clear to this reader why the Coriolis force should be zero at the equator. This is a tricky point to get over. Possibly the behaviour of a Foucault pendulum could be used; the authors do mention this but do not make the point that the rate of change of direction of swing varies with latitude. In the chapter 'Local influences and local weather' we read that 'in unstable air windward coasts enjoy no evening clearance of shower clouds'. Seaside landladies might prefer to see it pointed out that with unstable air in summer it is often possible to sit on a beach bathed in sunshine and watch the shower cloud building up inland.

But these are minor points. In the main the lay reader is given a clear impression of how synoptic meteorology works, from the making and collection of observations to the drawing and use of synoptic charts for forecasting. He is also shown how an appreciation of local influences may enable him to interpret a general forecast so that it is more directly useful to himself. A new chapter discusses briefly the highly topical subject of pollution in the atmosphere. The authors do not attempt too much over-simplification in that, for example, they describe a frontal model but point out that on a particular occasion an actual front may depart significantly from this model. It is thus possible for the general reader to understand why the professional forecaster does not achieve or expect to achieve complete accuracy on every occasion.

H. HEASTIE

Instant wind forecasting, by A. Watts. 225 mm × 165 mm, pp. 119, *illus.*, Peter Davies Ltd, 15–16 Queen Street, Mayfair, London W1X 8BE, 1975. Price: £2·90.

The title may evoke a reaction of horror or at least disbelief on the part of the professional meteorologist, but one has to recognize that there is today an increasing number of people whose recreation depends on or involves using the wind and who need some elementary guidance on its behaviour and predictability. The aim of this book is to provide this guidance and 'to help sort out the probable trends in the wind from a mass of possibilities' (page 6). It is written for the sailor, in particular the dinghy sailor.

The author, a one-time professional meteorologist, has no illusions as to the problems and difficulties in forecasting the wind, and he rightly restricts his discussion to short-term trends. Using photographs and word pictures representing a wide variety of weather situations he seeks to tabulate the likely changes. This is a task in which complete success is probably impossible, and even to attempt it is praiseworthy. Many of the tables provide good and comprehensive summaries of all the possibilities under a particular heading; for instance the table on pages 36 and 37 under the caption 'Will there be a big blow?'. Given a spare hour or two it is an interesting exercise to sample what may be

gleaned from them (hardly instant!). One enters the maze first of all by identifying the sort of day it is under 'the wind's day', then, turning to the page appropriate to that sort of day, the student is led into a series of tables showing the possible diurnal, local and micro changes to look for, and then on to the sections which deal with these changes in more detail.

The main drawback with the book is that in common with others of his recent publications the author seems to want to develop a mystique rather than an elementary understanding of the patterns of weather which he identifies. His essentially empirical approach to the subject might be justified for the particular audience which he has in mind were it not for his frequent use of semi-professional jargon which must be lost on the majority of readers: 'nocturnal polar airstreams', 'early katabatics', 'sea breeze frontal systems', to name but a few examples. What does he mean when he says 'cyclonic isobars inhibit sea breezes'? The sea-breeze is discussed at length but the various evidences of the breeze are not linked to any simple model which might help the reader to understand what they all mean; yet he is expected to be able to differentiate (page 9) between 'coastal slope winds', 'katabatic winds', and 'mountain and valley winds', as being sufficiently dissimilar one from another to require separate treatment.

The book is attractively produced and there are some good photographs, but most of the diagrams are poorly conceived and lack adequate captions. With this latest volume the author should be able to cash in on his earlier successes with *Wind and sailing boats* and *Instant weather forecasting*, and it is probably the best companion on the market at the moment.

D. M. HOUGHTON

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LETTERS TO THE EDITOR

The construction of 500-millibar charts for the eastern North Atlantic–European sector from 1781

Although Mr Kington (*Met Mag*, **104**, pp. 336–340) does not say exactly how he arrived at the thickness lines on his Plate II (he quotes nine separate factors as influencing his decisions) the resulting values over Scandinavia (for instance) are so improbable as to be virtually certain to be wrong by a large amount.

The extreme minimum of thickness in December over Stockholm in the period 1951–66 as quoted in *Geophysical Memoirs* No. 117 is about 504 decametres (dam) whereas Kington's value is near 480 dam with even lower values farther north. The surface temperature at Stockholm on 28 December 1783 was −15°C. I have examined the 1000–500-mb thickness values over Stockholm on the days when the temperature at midday at Stockholm in the 1960s was between −10° and −20°C. The mean thickness associated with these surface

temperatures was 510 dam with a standard deviation of 5 dam, so that Kington's 480 dam is about six standard deviations away from the mean thickness associated with the recorded surface temperature. Such a thickness value would be rare in December even over Siberia or northern Canada.

A temperature of −15°C at Stockholm in December is not so rare a phenomenon as to suggest that associated 1000–500-mb thicknesses would be similar to present-day extreme December values over Siberia.

I conclude that 510 dam is the most likely thickness value over Stockholm on 28 December 1783.

At the same time as these unprecedentedly low thicknesses were drawn over Scandinavia, values over Italy (for example) are within 6 dam of the maximum recorded in the period 1951–66. Mr Kingston's gradients over Europe are certainly much too strong.

An obvious check of the methods used could be made by preparing some 500-mb charts in the recent past and comparing with the real thing.

A more satisfactory method of producing thickness charts (and hence 500-mb charts) for years without upper-air data would be to carry out systematic regression analysis over a network of points, relating surface temperature to 1000–500-mb thickness in years for which data are available and then applying the regression equations to the earlier years. Perhaps this is what Kington intends in his method (a) (2) but Figure 1 does not suggest that he has carried this out rigorously.

Assistant Director (Synoptic Climatology), R. A. S. RATCLIFFE
Meteorological Office,
Bracknell.

Reply by Mr J. A. Kington:

In his letter, Mr Ratcliffe makes some criticisms of the contents of my paper on a method of constructing charts. In the following discussion these criticisms are answered with some of the points being clarified and expanded. A second illustrative example is given of a post-1950 case for comparison.

(a) The method of arriving at the thickness lines given in Figure 1 of my paper has been questioned. I agree that it was not made clear whether all or only some of the techniques listed under the heading Construction of 1000–500-mb chart were used in the drawing up of this chart. Firstly it should be realized that to construct a series of deduced 500-mb charts based on all the techniques given would require a fully operational program of work running in conjunction with my present project of preparing and analysing surface daily weather maps from 1781 and this at present is not in action. Indeed, the main object of my paper was to indicate the method with which it would be possible to construct a series of 500-mb charts from 1781. At the same time, however, I thought it would be a useful and interesting exercise to include an illustrative example, employing as many of the construction factors as are readily available to me at present, that is to say use of synoptic-climatological links between 1000–500-mb thickness and surface synoptic features such as standard pressure patterns, alignment and types of fronts and change-over zones in precipitation forms,

together with a consideration of the relationship between total thickness and wet-bulb potential temperature. Perhaps I should have made this point more clearly when presenting the chart.

(b) With regard to the statement 'the resulting values over Scandinavia (for instance) are so improbable as to be virtually certain to be wrong by a large amount', I would add that the extreme minimum of thickness in December over Stockholm in the period 1951–66 is given as 498 dam in Figure 4(l) on page 28 in *Geophysical Memoirs* No. 117 (Moffit & Ratcliffe, 1972) and not 504 dam as quoted by Mr Ratcliffe. However, although I agree that my value of 480 dam would be extremely subnormal, in view of the comments given below on the prevailing synoptic situation I cannot accept that it is wrong by a large amount.

In my original paper I only gave reference to the synoptic situation for 27 and 28 December 1783; however, from an examination of the daily weather maps for late December 1783 it is interesting to note that the general weather pattern which gave rise to the situation on 27th/28th began on 21st/22nd, when an anticyclone over central Europe moved north-eastward to become a blocking high over Scandinavia. Subsequently, high pressure also developed over the Norwegian Sea and Icelandic region on the 27th and 28th with cold-air advection westwards and south-westwards over the Low Countries, northern France and the British Isles. Minimum air temperatures in these areas fell to between −11 and −16°C and rivers and lakes became frozen over. The severe temperature regime of this airstream provides an indication of the very cold air that had been involved in the anticyclonic circulation over Scandinavia and also the probability that related 1000–500-mb thickness values would have been much below normal.

In a synoptic study of winter anticyclones over Scandinavia, Miles (1961) has stated that 1000–500-mb thickness anomalies associated with these systems were in general some 15 to 20 dam below normal during the first two days over the region. Thus assuming a mean value over Scandinavia of 528 dam in December (Moffitt & Ratcliffe, 1972), the minimum thickness over the region could have been about 510 dam by the 24th. This is in agreement with the value given by Mr Ratcliffe for the mean thickness associated with surface temperatures of −10 to −20°C over Stockholm. However, these estimates are based on generalized or mean values and in a particular situation displaying extreme characteristics, as that described above for 28 December 1783, I suggest that even lower thicknesses should be considered. Also, the possible effect of further cooling in a blocking situation over Scandinavia after the initial period should not be overlooked. For example, if overall cooling continued in the system at an equivalent rate of about 3 dam per day from 24 to 28 December, a value of 498 dam, that is to say, equivalent to the extreme daily minimum of the period 1951–66, or within −3 to −2 of Ratcliffe's mean value of 510 dam could have been obtained by 28 December 1783. The possibility that extreme values outside the limits of the 1951–66 analysis may have occurred in the past and for that matter could well occur in the future should not be ruled out. The main point of difference here seems to be whether we are dealing with a mean or extreme minimum, and I would suggest that the most likely thickness value over Stockholm on 28 December 1783 should be at least 12 dam lower than the estimate given by Mr Ratcliffe. However, the question would be more satisfactorily

resolved when and if a project utilizing all the techniques listed is put into operation.

(c) With reference to the statement that 'an obvious check of the methods used could be made by preparing some 500-mb charts in the recent past and comparing with the real thing', a post-1950 example has now been constructed using the same techniques that were available to me for drawing up the original illustrative example. The modern situation selected is that for 30 December 1962. Only surface data (extracted from the *Daily Weather Report*) which would have been available for preparing a daily weather map for the 1780s have been used. It will be seen from Figure 1 that despite 500-mb contour heights being generally

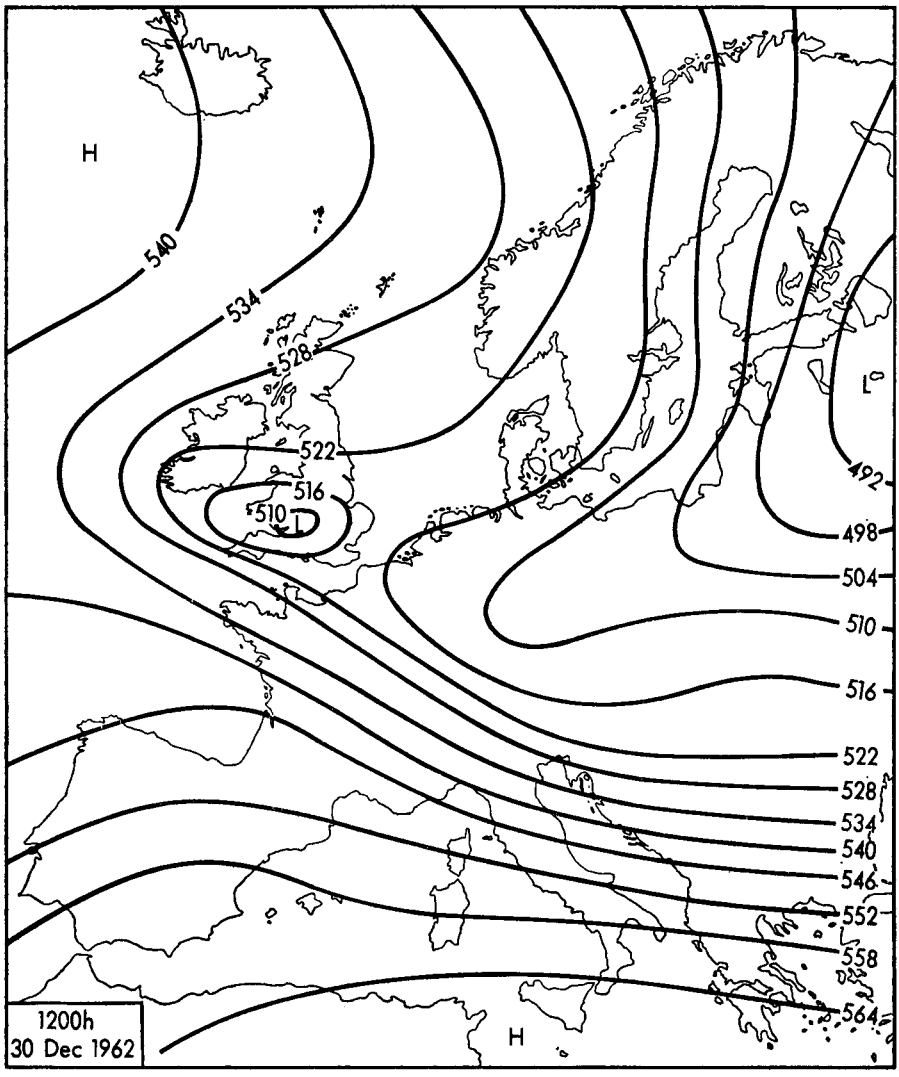

FIGURE 1—500-mb CONTOURS AT 1200 h ON 30 DECEMBER 1962 CONSTRUCTED WITH AVAILABLE TECHNIQUES BY J. A. KINGTON FROM THE METHOD DESCRIBED

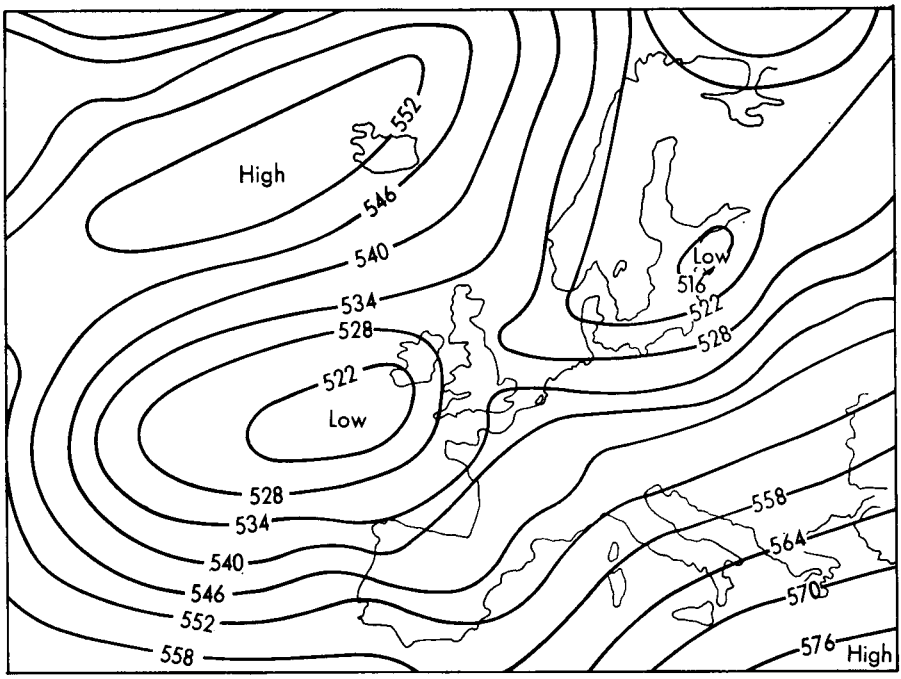

FIGURE 2—500-mb CONTOURS AT 0000 h ON 30 DECEMBER 1962
From the *Daily Aerological Record* of the Meteorological Office.

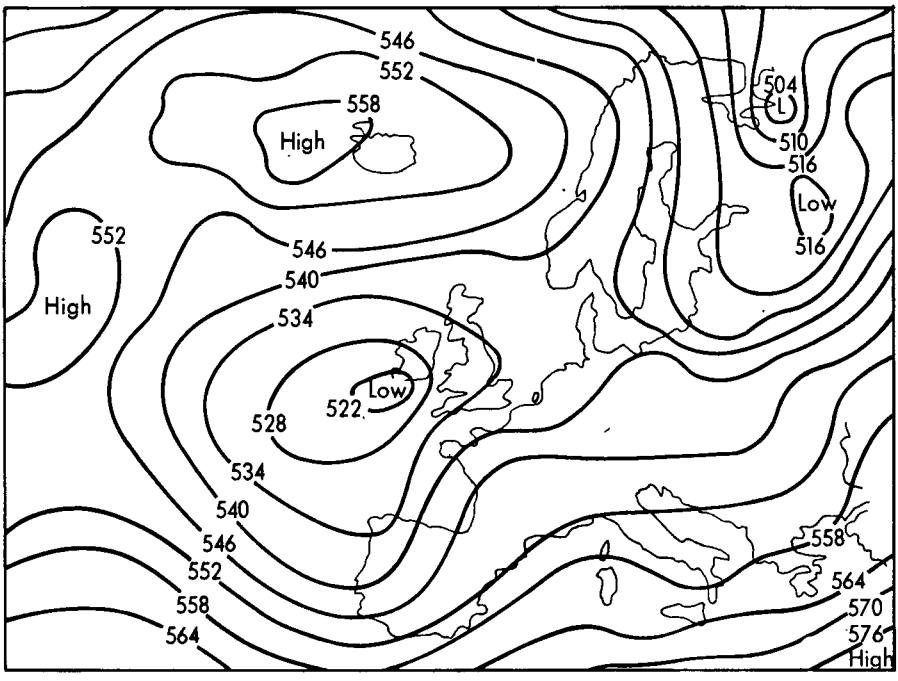

FIGURE 3—500-mb CONTOURS AT 0000 h ON 31 DECEMBER 1962
From the *Daily Aerological Record* of the Meteorological Office.

lower, the main features of the constructed pattern are similar to those of the actual patterns (see Figures 2 and 3). This reinforces my argument that even with a limited use of the techniques suggested a reasonable approximation of the general pattern can be obtained. How much more satisfactory it would be using all the techniques suggested!

(d) In his final paragraph Mr Ratcliffe states 'A more satisfactory method of producing thickness charts (and hence 500-mb charts) for years without upper-air data would be to carry out systematic regression analysis over a network of points, relating surface temperature to 1000–500-mb thickness in years for which data are available and then applying the regression equations to the earlier years.' This is indeed what was intended in section (a) (2) of my paper and I agree that it would be invaluable if 1000–500-mb thickness values at selected points, corresponding to present upper-air stations, could be related to air temperatures. In utilizing a method based on work by Boyden (1962), Parrey (1972) has devised a means of forecasting maximum temperatures from 1000–500-mb thickness values; from an analysis of surface and upper-air data for the five-year period 1964–68, a series of diagrams has been prepared in which the 1000–500-mb thickness at midday is related to maximum temperature, time of year, and winds from each of the four quadrants: north-east, south-east, south-west and north-west. From these diagrams, a sample of which is given in Figure 4, it is possible to read off maximum temperatures for as many days ahead as forecasts of 1000–500-mb thickness and surface pressure patterns are available. This is

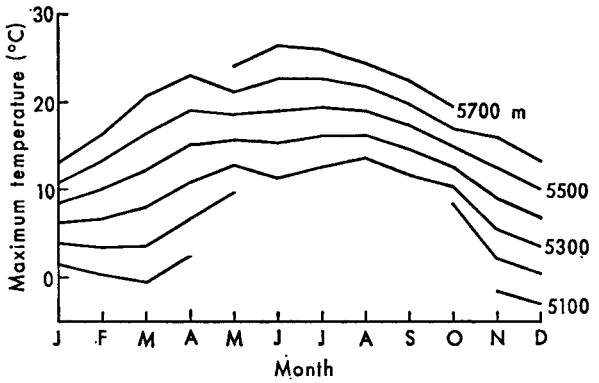

FIGURE 4—MAXIMUM TEMPERATURE RELATED TO 1000–500-mb THICKNESS FOR GEOSTROPHIC WINDS IN THE NORTH-WEST QUADRANT FOR EACH MONTH OF THE YEAR (From Parrey, 1962)

almost precisely the technique I had in mind for determining spot values of the 1000–500-mb thickness at a network of points corresponding to present upper-air stations since it would be equally possible to obtain from similar series of diagrams estimates of 1000–500-mb thickness values for as many days as surface historical weather maps at 14 h are available from 1781.

In conclusion, I should like to say that Mr Ratcliffe's criticisms have afforded me the opportunity to clarify certain points concerning the illustrative example and to enlarge upon the subject in general, for which I am grateful. However,

the main object in presenting my paper remains the same, that is to indicate that the material is available and techniques are possible for constructing a series of historical 500-mb charts from 1781 in order to lengthen the period over which a reasonable three-dimensional representation of the atmosphere can be obtained for use with synoptic-climatological and climatic-change studies.

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J. A. KINGTON

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CORRECTION

Meteorological Magazine, November 1975, p. 333, Figure 1: The ordinate axes should be labelled 'mW cm^{-2}' and the numerical values implied by the curves should be divided by 60.

OBITUARIES

It is with regret that we have to record the death of Mr K. Richardson, Senior Scientific Officer, Plymouth, on 17 October 1975, and of Mr D. F. Baker, Higher Scientific Officer, Boscombe Down, on 9 November 1975.

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked 'For Meteorological Magazine'.

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THE 1974/75 STRATOSPHERIC WINTER

By N. R. WATSON

SUMMARY

In August 1974 new definitions of stratospheric warming were proposed. These were used for the first time during the northern winter of 1974/75 by the Stratospheric Research Group at the Free University of Berlin in issuing STRATWARM alert messages. This paper describes the features of the stratospheric circulation in relation to the warmings of the winter. The examples of the circulation changes which occurred, mainly at 10 mb, were taken from the daily chart series prepared in the High Atmosphere Branch of the Meteorological Office at Bracknell.

Examples of the kinetic-energy changes and of the vertical motion in the stratosphere during warming periods are also presented.

THE STRATOSPHERIC-WARMING-ALERT SYSTEM

In November 1973 the Commission for Atmospheric Sciences (CAS) of the World Meteorological Organization (WMO) noted that adequate explanations of major stratospheric warmings were still not available and that the phenomenon had not been observed in sufficient detail. Although the stratospheric-warming-alert system had first been introduced during the International Year of the Quiet Sun (IQSY) in 1964, and much information had subsequently been accumulated about the warmings, there remained many outstanding problems. It was considered that studies of stratospheric problems would benefit from a concerted effort to gather as much information as possible during all stages of the winter warming period. A new and improved alert system would allow investigators to schedule observations during the times of maximum scientific interest. Consequently a Rapporteur was appointed by the CAS working group on stratospheric and mesospheric problems to review the criteria for STRATWARM alert messages and the observational program required on receipt of such messages. The Rapporteur in question, Dr Karin Labitzke, of the Free University of Berlin, met a working party composed of interested workers at Wallops Station, Virginia in August 1974, and new criteria were proposed for use in the 1974/75 northern winter. It was agreed that the Stratospheric Research Group of the Free University of Berlin would initiate daily messages on the 10-mb circulation, and issue the alerts when appropriate.

The new definitions for the warmings were formulated as follows:

(a) A warming is called MINOR if there is a temperature increase of at least 25 deg in a week or less, observed by balloon-sondes or rocketsondes, or inferred by radiances measured from satellites, at any stratospheric level in any area of the winter hemisphere. Warmings which do not meet this criterion may be said to be local warmings.

(b) A stratospheric warming is said to be MAJOR if at 10 mb or below* the latitudinal mean temperature increases polewards from 60°N *and* an associated circulation reversal is observed (i.e. net mean easterly winds are established north of 60°N).

A STRATALERT would therefore be issued when temperatures rose over an area by at least 25 deg in a week or less. A GEOALERT/STRATWARM alert message would be initiated when the temperature rose at least 30 deg in a week or less at 10 mb or below, or at least 40 deg above 10 mb.

The 10-mb level was chosen as the key level because it was the highest that could be analysed daily at Berlin with any degree of confidence. It was assumed that maximum use would be made of satellite radiance data, for example from the Selective Chopper Radiometer (SCR) instrument on NIMBUS E, and a communications link was therefore established between Oxford, where the SCR data are processed, and Berlin. These data provided an 'early warning' of the subsequent warmings at 10 mb by detecting them at higher levels.

The daily alerts were issued by Berlin at 1400 GMT, received by the High Atmosphere Branch at Bracknell by about 1430 GMT, and then distributed to interested groups in the United Kingdom.

On receipt of a STRATALERT message concerning a MINOR or MAJOR warming, the various meteorological rocket stations throughout the northern hemisphere agreed to fire rockets at an increased rate. Firing rates of up to three times a week were thought to be necessary, depending on the location of the warm area in relation to the rocket station. The Metrocket Group of the High Atmosphere Branch at Bracknell fired a total of 22 SKUA rockets during two detachments to West Geirinish, South Uist, in December 1974 and January–February 1975. The rocketsonde observations (ROCOBs) provided information up to about 65 km, but only data obtained below about 30 km (10 mb) were used in the daily series of charts produced by the Stratospheric Analysis Group in Bracknell.

STRATOSPHERIC ANALYSIS

Daily charts of the northern hemisphere at 50, 20 and 10 mb for 00 GMT have been drawn by the Statospheric Analysis Group of the High Atmosphere Branch since April 1974. These charts are drawn from radiosonde data and, when available, ROCOBs, but no satellite data are used. The ROCOBs are very valuable in the determination of the wind field at 10 mb, and especially so over the polar cap, since few radiosondes reach that level during the winter. The paucity of observations at 10 mb means that it may be 10 days or more before an individual chart is completed and the analyst is confident that continuity of flow pattern has been achieved. It is from this series of charts, mainly at 10 mb, that the major features of the 1974/75 winter stratospheric circulation will be discussed.

*Here and in similar contexts throughout this paper 'below' is to be interpreted as meaning 'nearer to the surface of the earth' and not 'at heights corresponding to numerically lower pressures'.

10-MILLIBAR CIRCULATION CHANGES

(a) *Summer to winter*

The normal summer-time circulation above about 20 mb consists of a generally easterly flow round a warm anticyclone centred over the pole. The wind field near the equator is dominated by the quasi-biennial oscillation and in the summer of 1974 was easterly and about 60 kn at 20 mb, and was changing rapidly from easterly to westerly at 10 mb.

Figure 1 (adapted from Murgatroyd, 1970) shows the mean summer and winter zonal wind and temperature conditions to be expected.

The warmest air occurs at about 1 mb (47 km) over the summer pole, while at 10 mb the temperature is about −25°C at the pole, and decreases steadily to about −50°C at the equator.

In mid July 1974 the 10-mb anticyclone was symmetrically placed over the pole with a central height of 32 300 gpm and an easterly wind of 20–25 kn over the United Kingdom.

By late August the high had declined to 31 500 gpm and had moved to Alaska, as small cold pools began to appear in mid latitudes. The first sign of the polar vortex appeared in mid September near Novaya Zemlya, and it deepened and moved eastwards round the pole. By the end of September it lay over the Canadian Arctic at 30 480 gpm (−55°C), while the remains of the summer high were displaced across the Pacific and north-west Atlantic (−45°C).

Cooling continued during October with further deepening of the polar vortex down to 29 760 gpm in early November over Greenland and with temperatures falling to −68°C. During November the main low split and then reamalgamated with troughs swinging eastwards across Siberia and Alaska. It was late in the month when the Aleutian anticyclone became finally established after the eastward passage of such a trough into the U.S.A. By early December the 10-mb circulation reached its 'classical' winter state with a minimum height of 28 560 gpm near Novaya Zemlya, and a maximum of 31 080 gpm over the Aleutian Islands. The coldest air, −75°C, lay just to the west of the vortex, with the warmest air (−35°C) over China and Kamchatka (Figure 2).

(b) *Early winter warming*

The first minor warming alert was issued on 14 December when temperatures over southern Europe rose to about −25°C. Figure 3 shows the changes in the temperatures at 30, 20 and 10 mb during the period 10–19 December 1974 at Vienna. The 10-mb temperature rose 35 deg in about four days and then fell back to its original value; the 20-mb temperature showed only small fluctuations while the 30-mb temperature change was in the opposite sense to that at 10 mb. The cause was a temperature wave that crossed the Atlantic from the Caribbean and then moved farther east into Asia. As this warm wave was moving east over the Atlantic, the 10-mb trough over Canada was intensifying so rapidly that from 8 to 15 December it developed into the major low as it moved from the Canadian Arctic north-eastwards to Spitsbergen. The original low which at the beginning of the month was near Novaya Zemlya degenerated into a trough which weakened rapidly as it rotated eastwards.

These rapid changes at 10 mb were probably indicative of much more violent changes in the middle and upper stratosphere. On 13 December the rocketsonde observation at West Geirinish showed a belt of extremely strong wind at 55 km;

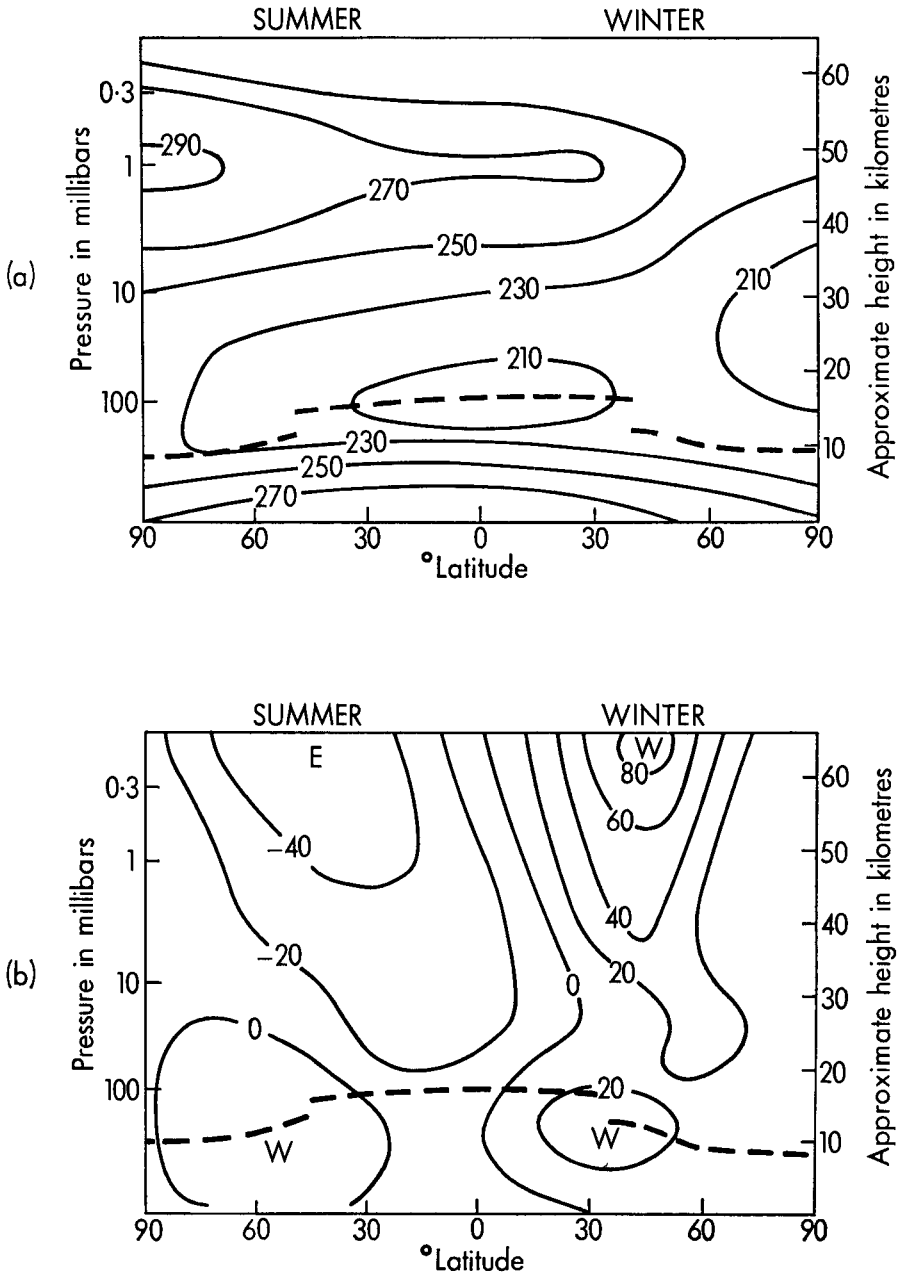

FIGURE 1—LATITUDINAL MEAN CROSS-SECTIONS OF TEMPERATURE IN KELVINS (a) AND ZONAL WIND SPEED IN METRES PER SECOND (b) FOR THE SOLSTICES
The thick dashed lines represent the tropopause. In the lower diagram E denotes 'easterly' and W 'westerly'. (Adapted from Murgatroyd, 1970.)

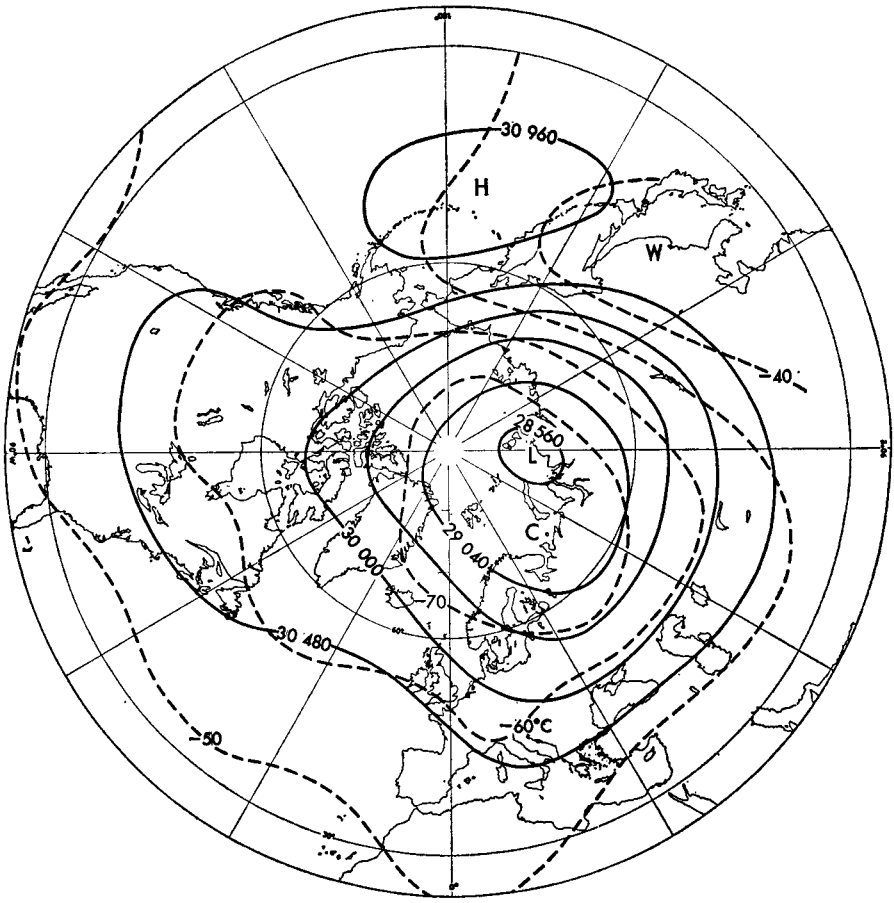

FIGURE 2—CHART FOR 10 MILLIBARS AT 00 GMT ON 2 DECEMBER 1974
——— contour heights at intervals of 480 gpm
– – – isotherms at intervals of 10 deg

the wind and temperature profiles are shown in Figure 4. The maximum wind speed of 173 m/s (≈335 kn) at 55 km (the mean between 54 and 56 km) is very near to the highest ever recorded over Scotland.

From 18 to 26 December the 10-mb vortex (28 300 gpm) near Novaya Zemlya and the Aleutian High (31 080 gpm) remained stationary and very strong north-westerly winds (≈150 kn) blew across the Canadian Arctic.

(c) *Mid-winter warming*

Just before Christmas the first signs of the warming appeared in the satellite data. Radiances in the B_{12} and B_{23} channels of the SCR showed maxima over Europe which moved eastwards with time. By 26 December the temperature increases at 10 mb reached minor warming proportions over China and south Siberia, and by 1 January 1975 the warmest air (−8°C) was located over central

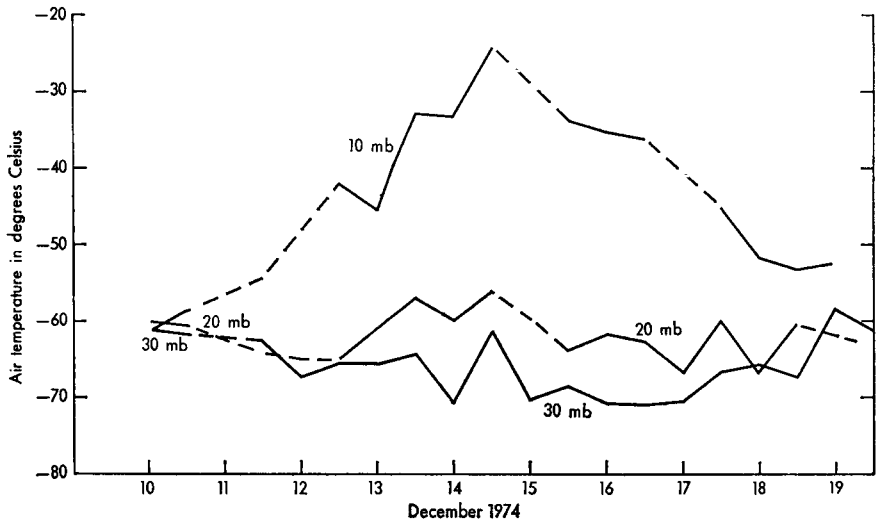

FIGURE 3—TEMPERATURE CHANGES AT VIENNA CAUSED BY MINOR STRATOSPHERIC WARMING
The dashed portions of the traces denote interpolation or extrapolation.

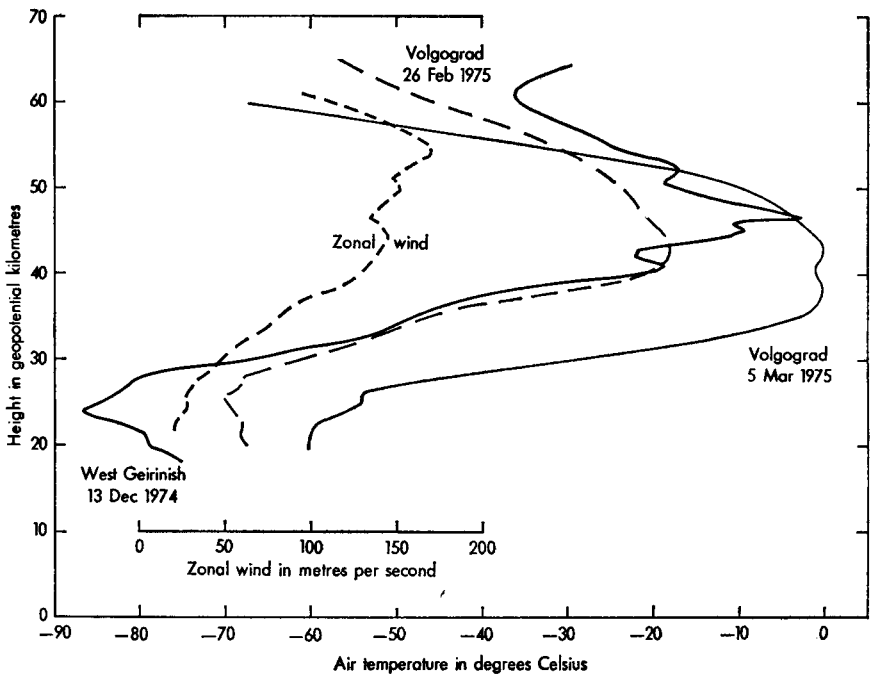

FIGURE 4—TEMPERATURE AND ZONAL WIND PROFILES AT WEST GEIRINISH ON 13 DECEMBER 1974, AND TEMPERATURE PROFILES AT VOLGOGRAD DURING AND AFTER THE FINAL WARMING

Siberia. The subsequent rise in contour heights over central and western Asia caused the vortex to weaken and move south-west to northern Sweden by 7 January. Between 1 and 7 January the warm air had moved north-eastwards to the Canadian Arctic, raising the 10-mb temperature over the North Pole to −28°C. The reversal of the meridional temperature gradient occurred by 3 January and the maximum temperature was located over the pole by 9 January.

Although the air over the Arctic then began to cool, warming still occurred over the Atlantic and Europe. Temperatures over central Europe rose from −72°C on 9 January to −55°C on 18 January, and a high cell (30 720 gpm) appeared over the central Atlantic. This cell moved eastwards across Europe and declined over Turkey by 24 January.

The pronounced wavenumber two pattern, which sometimes occurs shortly after warmings, showed up well on 20 January, with the European and Aleutian highs and two lows, one over Canada and the other over Siberia (Figure 5). Later in January the Siberian low declined into a trough, leaving the main vortex (28 800 gpm) over north Greenland. It is interesting to note that on 1 January the highest and lowest temperatures on the 10-mb chart were −15°C and −82°C, a difference of 67 deg. As a result of the warming, by the end of the month this difference had declined to 20 deg, i.e. −45 to −65°C. These temperature changes can be plainly seen in Figure 6 which shows cross-sections over the pole and along the Greenwich Meridian.

The effect of the warm air to the north was to reduce the westerly flow at 10 mb owing to the easterly thermal winds that were established. Although the 10-mb zonal wind at 60°N decreased by one-half in a week (29 December to 5 January (Figure 7)), it did not become easterly, so no 'major warming' occurred. However, a major warming did occur at 1 mb (48 km), where easterly winds were blowing to the north of 65°N by 2 January (Labitzke, 1975).

Early in February, further anticyclonic development over the United Kingdom and the Aleutians split the main vortex into two centres, over Hudson Bay and Siberia. The U.K. high collapsed by 11 February and allowed a strong westerly flow to spread across Europe. The Hudson Bay centre degenerated into a trough by 15 February and swept eastwards across the north Atlantic so that by 22 February one main symmetrical vortex remained near Heiss Island (80°N 58°E) and the mean zonal wind at 60°N reached the highest level of the winter (see Figure 7). By 25 February the temperature over Scandinavia had fallen to −70°C again but the satellite data showed warm air to be present high over central Russia.

(d) *The final warming (27 February–17 March)*

The first indication of the final warming was the development of a warm area (−40°C) over Manchuria at 10 mb on 24 February. This area moved north-west across the wind flow and became steadily warmer over the next few days. A minor warming alert was issued on 27 February for the area near 58°N 110°E. For the next two to three weeks the warmest air at 10 mb moved little from this position, reaching a maximum temperature of −5°C on 3 March. The warm air began to move north-eastwards from Siberia on 26 February and the first warm pulse reached the pole on 10 March. The warm air, spreading up to and over the pole, can be seen in Figure 8, which shows the time variations of the 10-mb temperatures on a section from 50°N 90°W to 50°N 90°E. In the middle of the warming the 10-mb temperatures over some areas of the Russian Arctic rose by

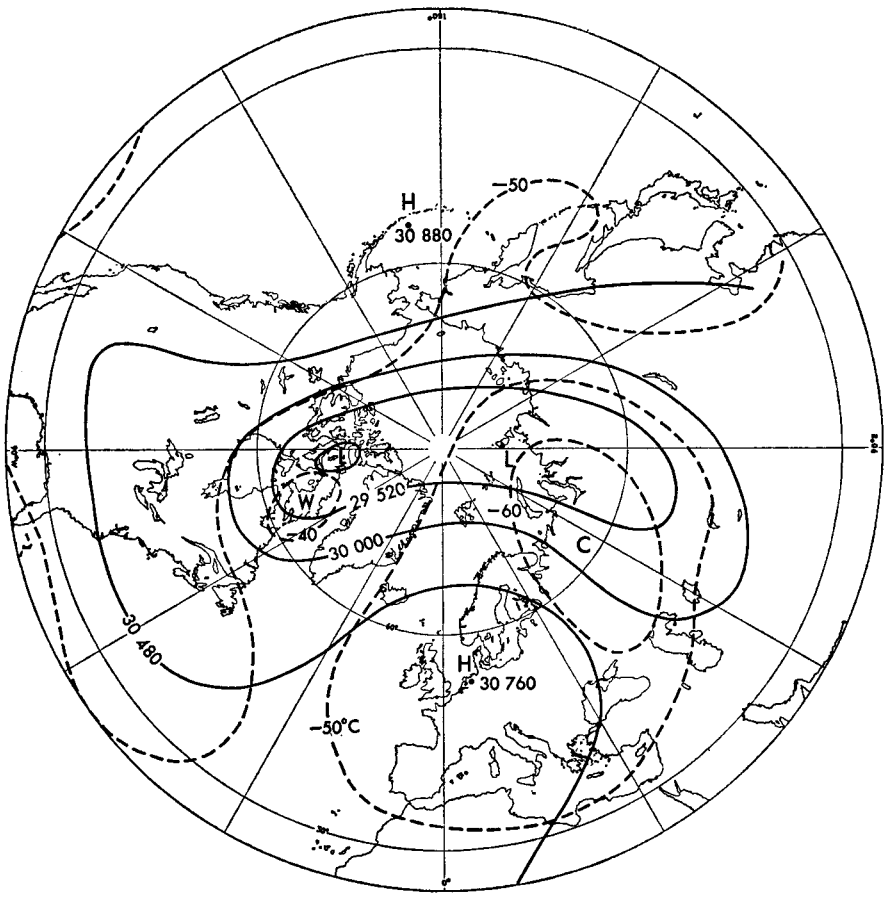

FIGURE 5—CHART FOR 10 MILLIBARS AT 00 GMT ON 20 JANUARY 1975
——— contour heights at intervals of 480 gpm
– – – isotherms at intervals of 10 deg

over 30 deg in a week. The 10-mb zonal mean temperatures during the final warming are shown in Figure 9. The meridional temperature gradient on 24 February was about 0·5 deg/degree of latitude at 70°N, by 6 March the temperature gradient was about zero, and then it became positive (i.e. a normal summer situation). Figure 10 shows two vertical temperature sections over the pole and through the Greenwich Meridian during and after the warming. Comparisons between these and sections for the mid-winter warming (Figure 6) are interesting. Although the initial conditions on both occasions were similar, the results were substantially different. The mid-winter warming produced an almost isothermal temperature field at 10 mb (≈30 km) but a cold polar core was maintained at 50 mb (≈20 km). The final warming, however, extended down throughout most of the polar stratosphere and produced a temperature section very similar to summer conditions. The extent of the warming in the upper stratosphere can be

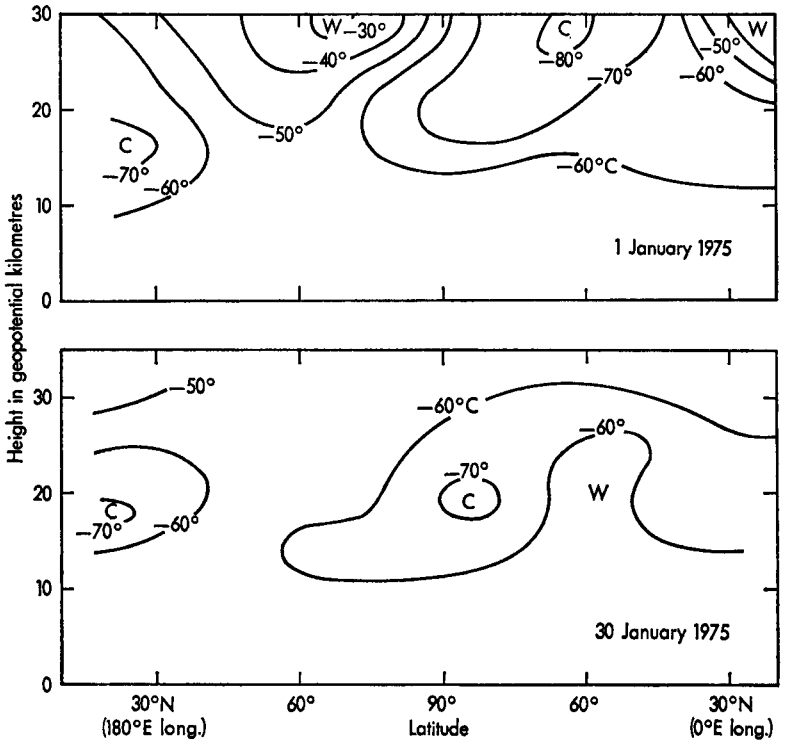

FIGURE 6—TEMPERATURES ON A LATITUDE–HEIGHT CROSS-SECTION ALONG THE 0°–180° MERIDIAN DURING AND AFTER THE MID-WINTER WARMING

seen in the temperature profiles from the rocketsonde observations at Volgograd (49°N 44°E) (Figure 4). Between 26 February and 5 March the air below 55 km became warmer (at 35 km by as much as 40 deg) as the stratopause descended to 40 km and increased in temperature to 0°C.

The final warming had the pattern of a simple wavenumber one type with the Aleutian high moving steadily northwards to the pole as the vortex filled and slipped southwards across Russia.

The effect on the geopotential heights between 28 February and 18 March is most striking (see Figures 11(a) and 11(b)). The main vortex (28 400 gpm) near 75°N 80°E began to fill and move westwards immediately the warm air appeared over China. The Aleutian high intensified and began to edge north-eastwards as the warm air moved across northern Alaska. By 16 March both the vortex (29 530 gpm) and high (31 300 gpm) were equidistant from the pole at 70°N, north-easterly winds at 30 mb were flowing over Scotland, and the zonal mean wind at 60°N had nearly turned to easterly (Figure 7). All three criteria have been used independently by workers in the past to define the final warming, but at present no official definition of the final warming exists. The sixteenth of March occurs in the 15th pentad of the year and according to Ebdon (1972) only once, in 1959, has the final warming occurred earlier.

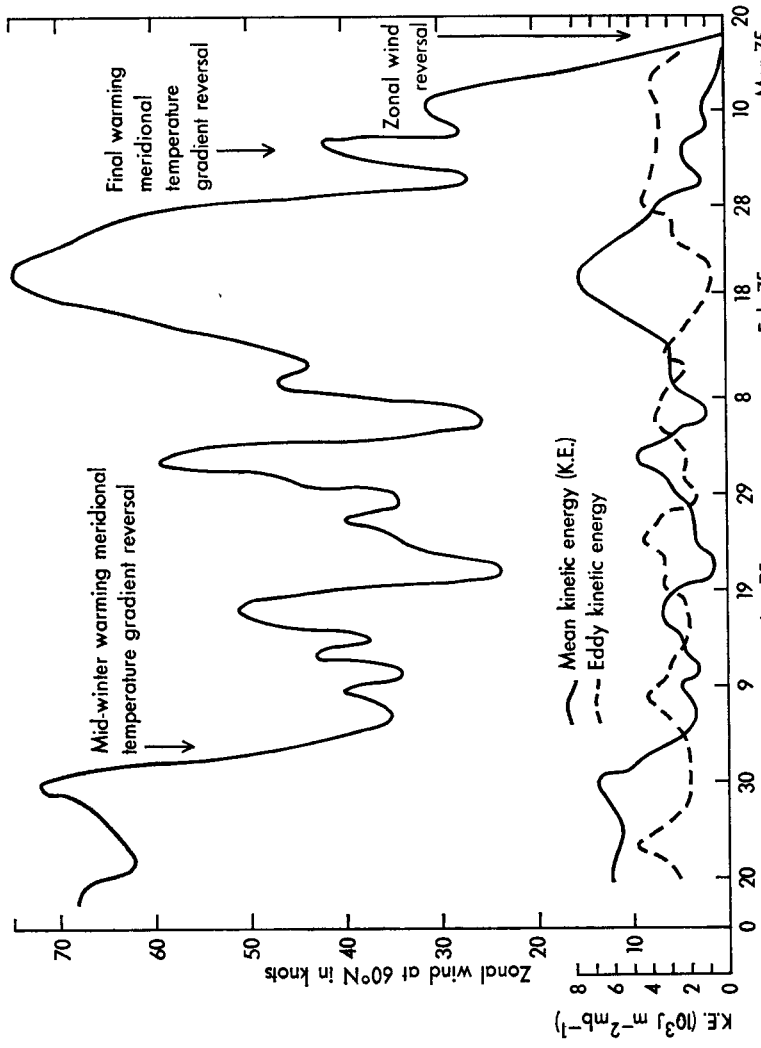

FIGURE 7—THE 10-MILLIBAR ZONAL WINDS AND KINETIC ENERGIES AT 60°N DURING THE 1974/75 WINTER

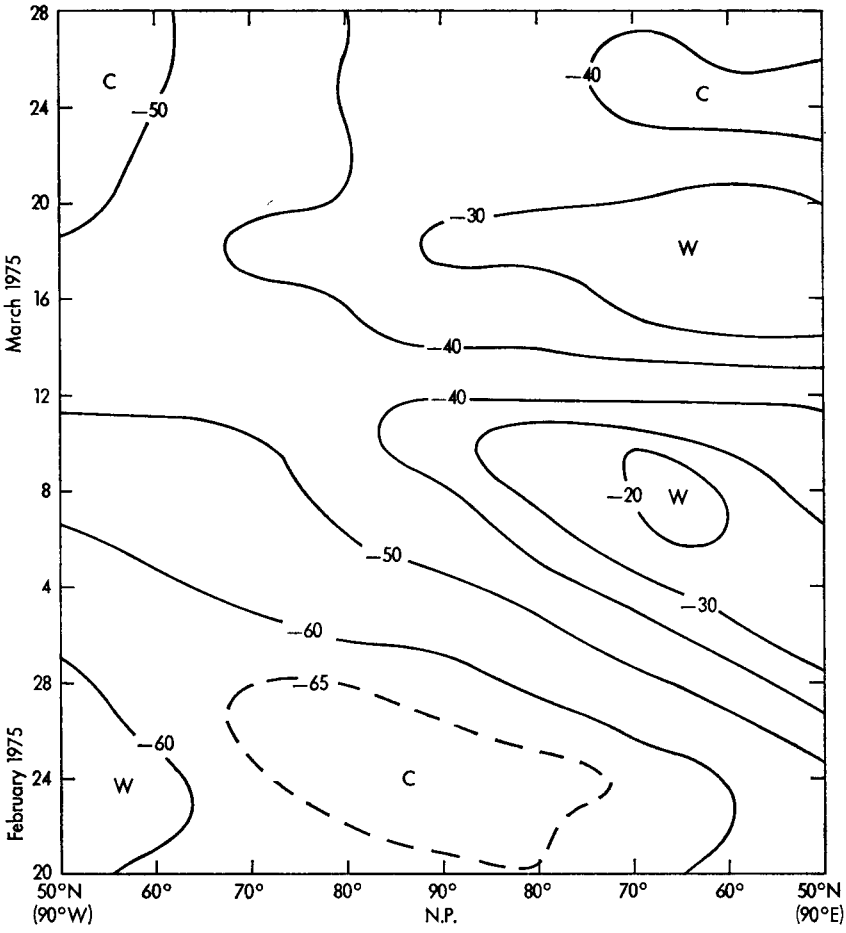

FIGURE 8—TEMPERATURE AT 10 MILLIBARS IN DEGREES CELSIUS IN SECTION OVER THE NORTH POLE DURING THE FINAL WARMING

By the end of March the high (31 450 gpm) was centred at 80°N 120°W and the low had filled to 30 300 gpm at 50°N 65°E. Air warmer than −45°C extended from central Asia across the pole to Greenland and the Canadian Arctic, and a strong mean easterly flow was present north of 60°N. The strong winds eased in mid April when the air over the polar cap cooled a little and did not increase again until May.

KINETIC ENERGY CHANGES DURING THE WINTER

During the winter, measurements were made daily of the mean and eddy kinetic energies (KE) at 60°N. The definitions of these terms are:

$$\text{mean KE} = \tfrac{1}{2}([u]^2 + [v]^2)\,(100/g) \quad \text{J m}^{-2}\,\text{mb}^{-1}$$

$$\text{eddy KE} = \tfrac{1}{2}(\overline{u^{*2}} + \overline{v^{*2}})\,(100/g) \quad \text{J m}^{-2}\,\text{mb}^{-1},$$

where the wind components at any point are given by

$$u = [u] + u^* \text{ and } v = [v] + v^*.$$

$[u]$ and $[v]$ are the zonal means, and u^* and v^* are the deviations from the means expressed in metres per second.

In general $[u] \gg [v]$ and for the average winter circulation at 10 mb, the mean KE is greater than the eddy KE.

However, during periods of stratospheric warmings, the increases in contour height over certain locations are substantial and they have the effect of increasing the local meridional wind speed and hence the eddy KE. Figure 7 also shows the mean and eddy KE at 10 mb at 60°N, plotted every day from mid December to late March. On the assumption that the conditions at 60°N represent those over the winter polar cap, the features of the winter, already discussed, can be detected in the changes in the mean and eddy kinetic energies.

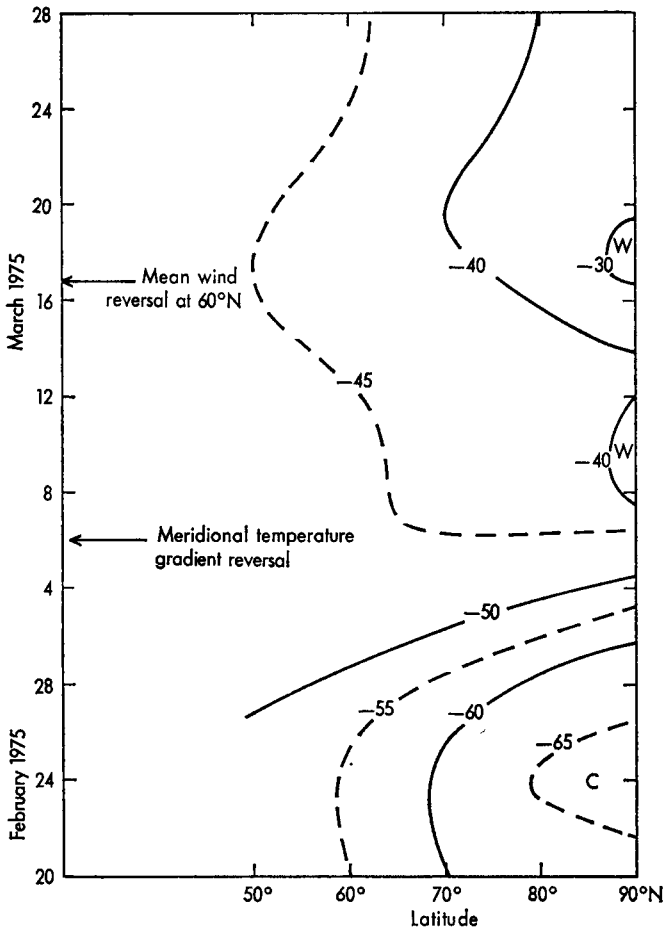

FIGURE 9—ZONAL MEAN TEMPERATURES AT 10 MILLIBARS IN DEGREES CELSIUS DURING THE FINAL WARMING

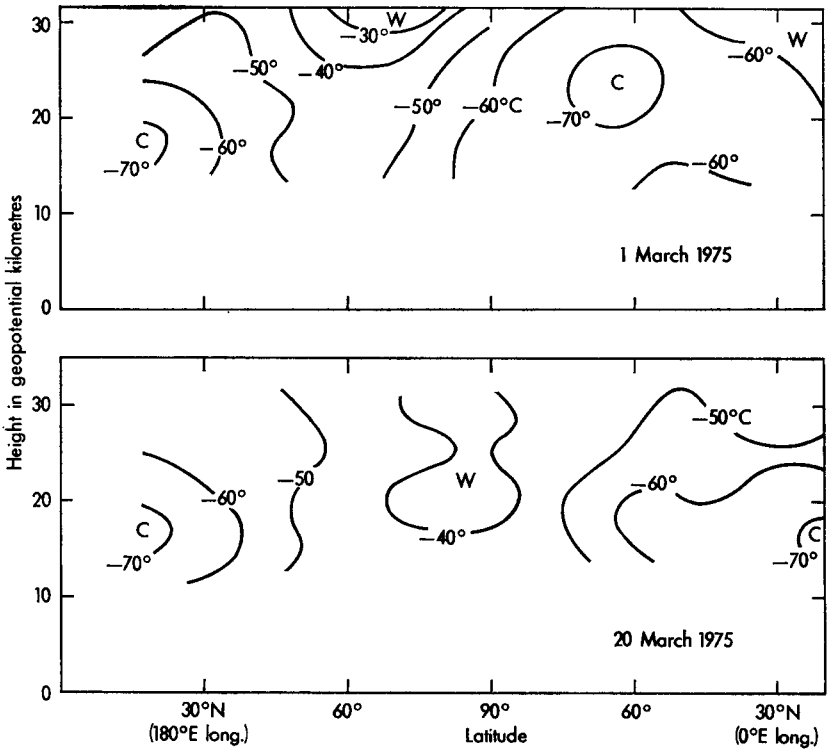

FIGURE 10—TEMPERATURE SECTIONS ACROSS THE NORTH POLE DURING AND AFTER THE FINAL WARMING OF 1975

During late December the mean KE built up to a maximum and then rapidly decreased during the period of the mid-winter warming. It then slowly increased to the highest of the winter (21–22 February) in a series of oscillations of increasing amplitude until finally there was a rapid loss of mean energy during the final warming.

The variation in the eddy KE is not as great as that of the mean, but it shows some marked periodicities and is generally out of phase with the mean KE. This is most apparent during January and February when the mean KE is increasing. A Fourier analysis of the eddy KE indicated a marked periodicity of about 15 days. This period has been noted before (Finger *et alii*, 1966 and Miller, 1967) with the suggestion that there was a lunar tidal effect influencing the stratospheric circulations.

Vertical velocity analyses

The fact that day-to-day changes in the temperature pattern are generally not great despite the large horizontal wind speeds implies that the air has a significant vertical motion over much of the winter hemisphere. In order to display the three-dimensional nature of the flow, isentropic analyses were carried out during the winter for the 350°C potential-temperature surface which lies between 20 and

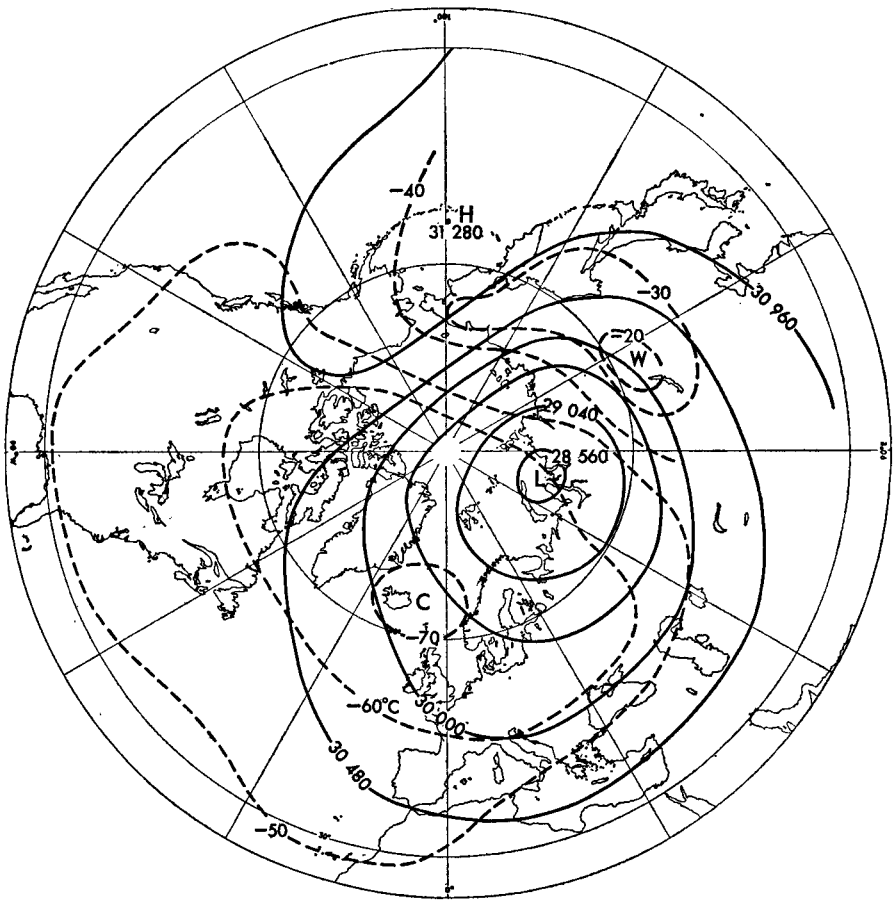

FIGURE 11(a)—CHART FOR 10 MILLIBARS AT 00 GMT ON 28 FEBRUARY 1975
——— contour heights at intervals of 480 gpm
– – – isotherms at intervals of 10 deg

30 mb. Figure 12 shows one such analysis for 28 February 1975, at the start of the final warming, on which streamlines and the height of the isentropic surfaces are drawn. The isentropic height field shows a high over the north-western Atlantic and a low over north-eastern Asia. The streamlines indicate that air passing near the centre of this low was displaced vertically by about 3 km, while ascending and moving over the pole to the North Atlantic. This ascent took about two days, while the descending air, moving more slowly over Europe and central Asia, took three days to return. During the descent into the Asian low, the air warmed up at the rate of about 15 deg per day, and it cooled at about 25 deg per day as it ascended over the pole. This cooling rate is at least an order of magnitude greater than can be expected by consideration of radiational cooling alone.

An estimate was made of the vertical velocities involved, on the assumption that the flow was adiabatic and that the general pattern did not change significantly from day to day. The main area of rising air on 28 February was located

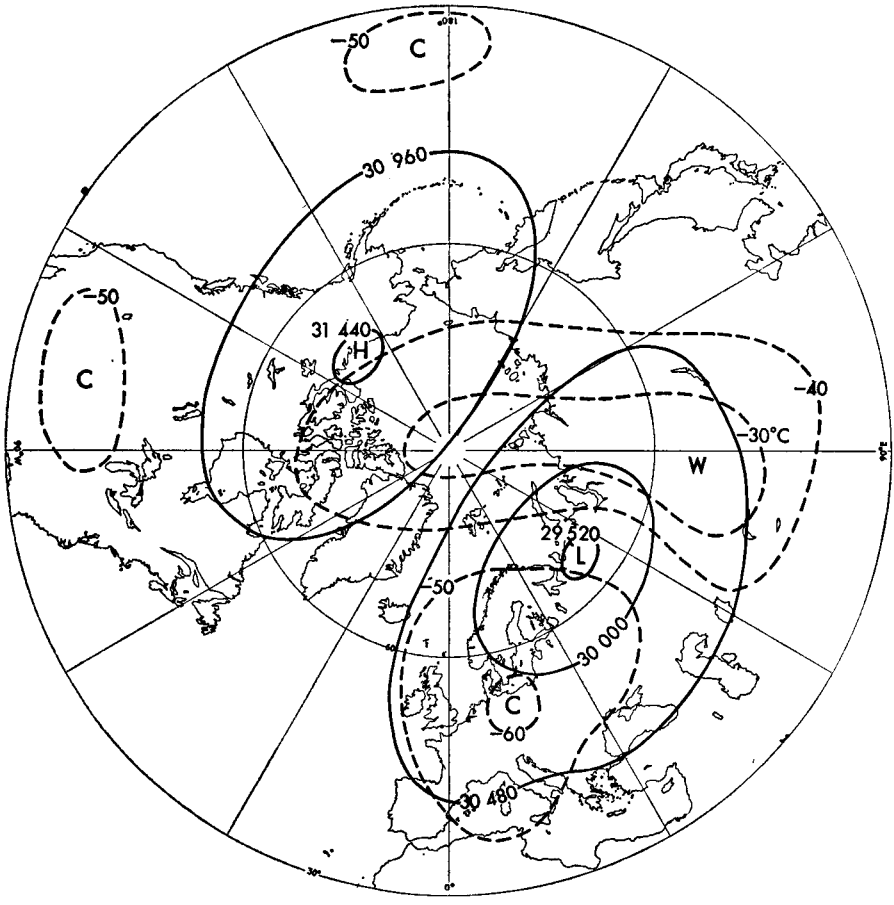

FIGURE 11(b)—CHART FOR 10 MILLIBARS AT 00 GMT ON 18 MARCH 1975
——— contour heights at intervals of 480 gpm
– – – isotherms at intervals of 10 deg

to the north of Alaska with a maximum vertical velocity of about 4 cm/s, while the core of the descending air was over central Asia with a vertical velocity of −2·5 cm/s. It was found that the area north of 80°N was occupied entirely by ascending air. In fact, when zonal means of vertical velocity are calculated with corrections for the slight height-field changes with time, ascent is seen to have predominated north of about 65°N, with a maximum value of over 2 cm/s at the pole (Figure 13). This meridional profile during a warming is consistent with a two-cell structure described by Perry (1967) with ascent at low and high latitudes and descent in middle latitudes. Also shown in Figure 13 is a similar profile for 17 March when the final warming was well advanced and the vertical velocities were decreasing.

Conclusions

The new alert system worked well in the 1974/75 northern winter. High-level data were very useful in its application, since without these data the analyst had

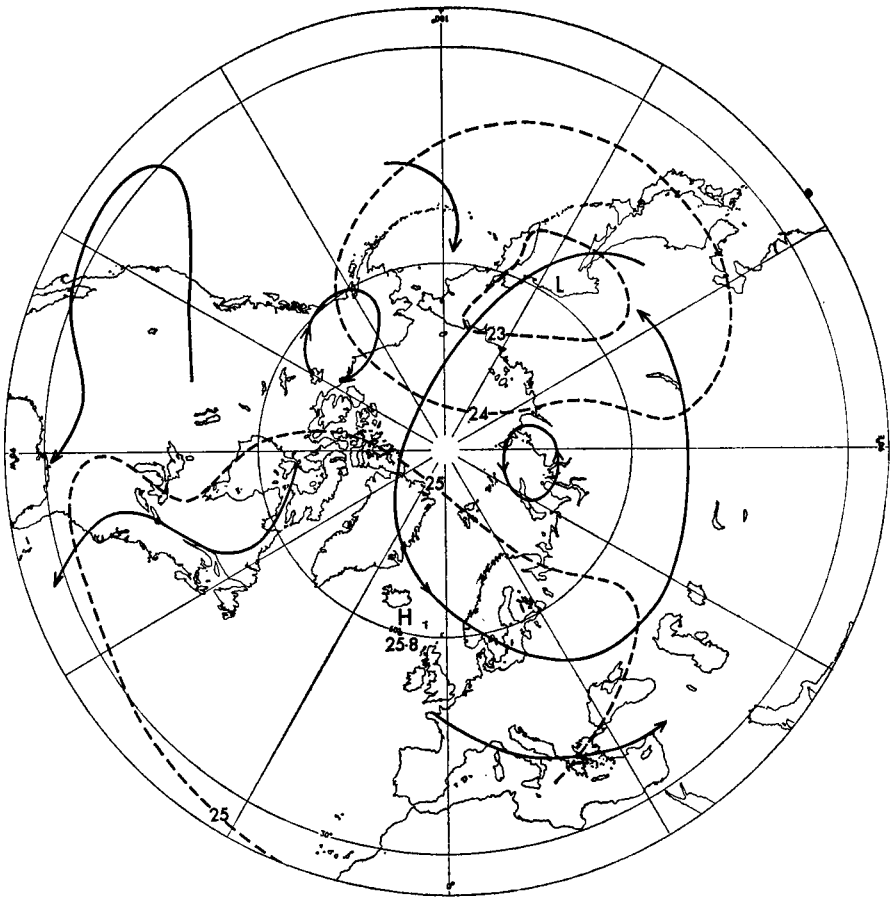

FIGURE 12—ISENTROPIC ANALYSIS FOR THE SURFACE $\theta = 350°C$ AT 00 GMT ON 28 FEBRUARY 1975

Solid lines represent streamlines. Broken lines represent the height of the surface in kilometres.

no knowledge of any warming until it reached radiosonde levels or had been intercepted by a rocketsonde. Access to satellite data is therefore a prerequisite of any useful stratospheric alert system.

Even though no major warming occurred below 10 mb, the 1974/75 winter contained many interesting features. The very early final warming, together with the westerly phase of the quasi-biennial oscillation have been shown by Ebdon (1975) to be important factors in determining the following summer's weather over south-east England. The hot, dry summer of 1975 certainly confirmed Ebdon's earlier suggestions.

Further study of the mid-winter and final warmings, especially of the vertical motions present in the atmosphere, is continuing.

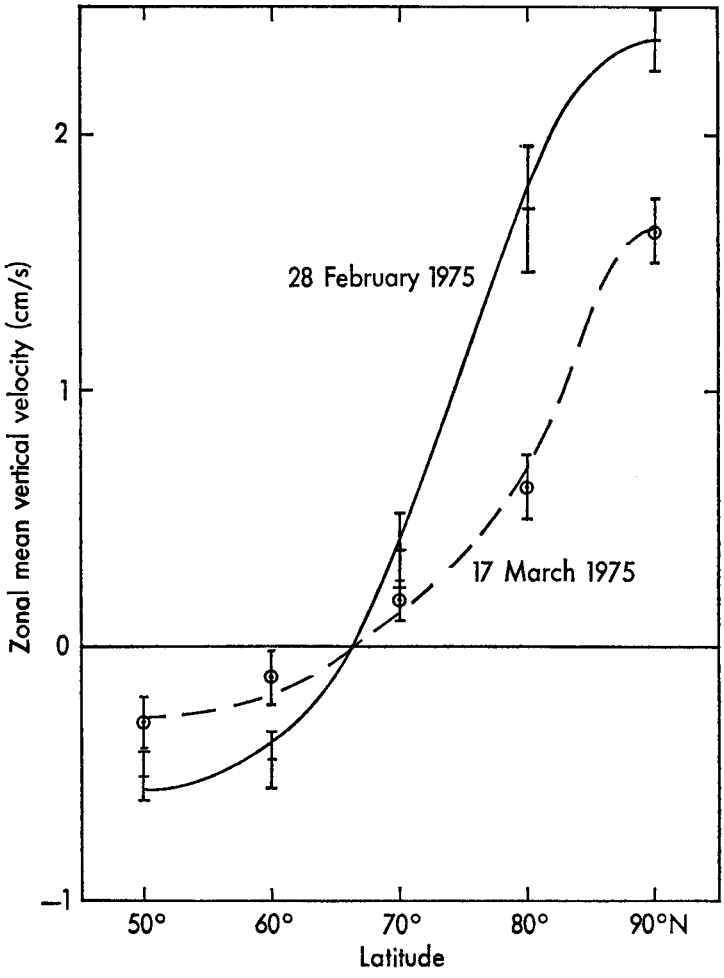

FIGURE 13—VARIATION OF ZONAL MEAN VERTICAL VELOCITY WITH LATITUDE
Standard errors of estimates are indicated by vertical lines.

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551.5:06(6):551.507.352

THE CURRENT WORK OF THE METEOROLOGICAL RESEARCH FLIGHT

By D. G. JAMES and J. M. NICHOLLS

(Meteorological Research Flight, Royal Aircraft Establishment, Farnborough)

SUMMARY

It is now almost 10 years since Aanensen and Grant described the work of the Meteorological Research Flight (MRF) in the mid sixties. Since then there have been changes in staff, in aircraft, and in the research program of the unit, and this paper, a modification of that recently presented to the Atmospheric Environment Committee of the Aeronautical Research Council, attempts to bring the account up to date.

The paper briefly describes the two aircraft at present in use by the MRF together with their instrumentation, and the types of research program on which they have been and are being used.

INTRODUCTION

The Meteorological Research Flight (MRF) is a unit of the Meteorological Office established to conduct atmospheric research from aircraft. It forms part of the Directorate of Research and reports directly to the Deputy Director of Physical Research. The flight has been located at the Royal Aircraft Establishment (RAE) at Farnborough in Hampshire since 1946. RAE provide the maintenance crews for the aircraft and, needless to say, a vast amount of scientific expertise in aircraft instrumentation and operation. The aircraft are loaned to us by the Royal Air Force who also attach a unit of aircrew—at present three pilots, two navigators and two engineers—to fly the aircraft and to look after the operational side of the flight. The Royal Air Force also provide our buildings and allocate funds for their upkeep and improvement.

The civilian staff of the MRF, numbering about 25, are employed by the Meteorological Office. Only four of this number are 'first-grade' scientists; the remainder, forming the 'facilities' side of the flight, include workshop staff, electronics engineers and computer programmers. Most of the staff are expected to fly, total flying hours being in the region of 600–700 hours a year. As can be seen, there are not enough scientists at MRF to justify this amount of flying, and indeed most of our work is performed for outside users, chiefly the Cloud Physics Branch of the Meteorological Office, hereinafter referred to as the C.P.B.

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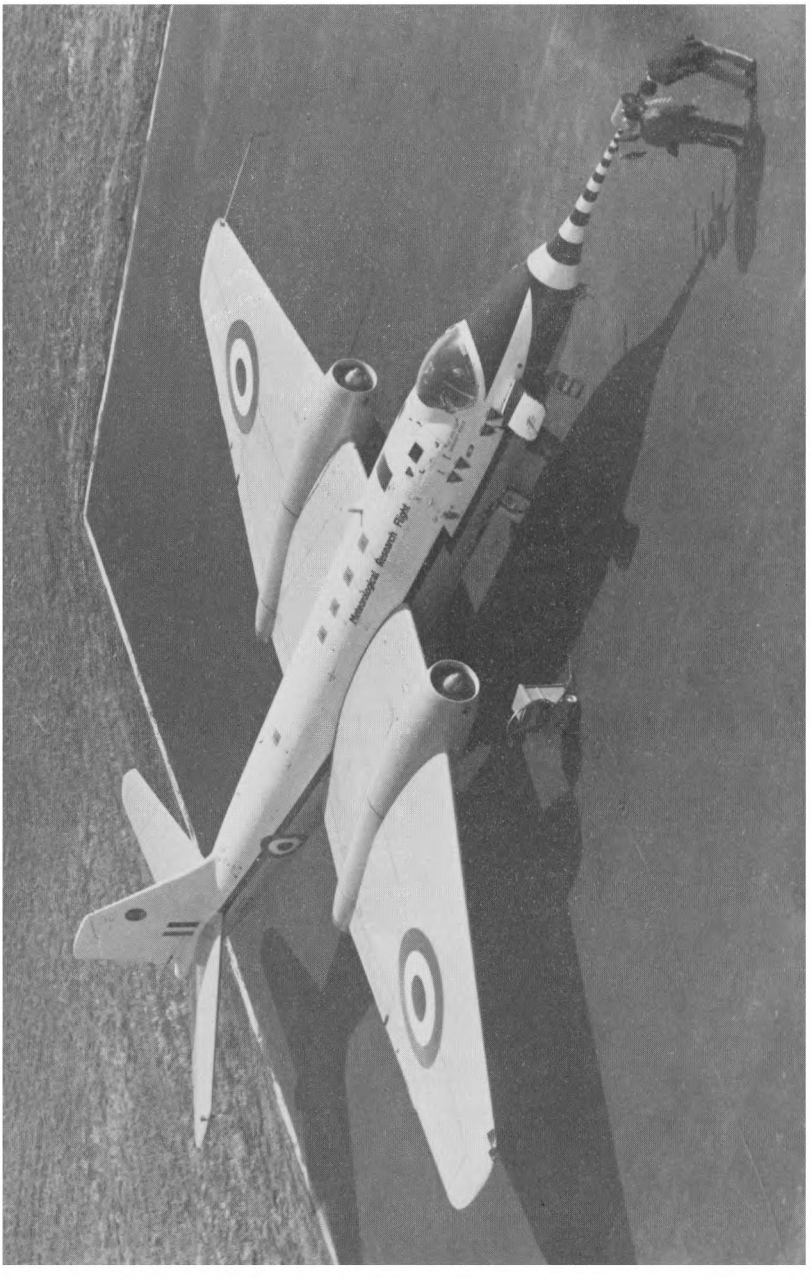

PLATE I—THE CANBERRA AIRCRAFT OF THE METEOROLOGICAL RESEARCH FLIGHT

PLATE II—THE HERCULES AIRCRAFT OF THE METEOROLOGICAL RESEARCH FLIGHT

PLATE III—PRESENTATION OF L. G. GROVES MEMORIAL PRIZES AND AWARDS, 14 NOVEMBER 1975

Left to right: Mr J. M. Nicholls, Dr R. J. Murgatroyd, Major K. G. Groves, Squadron Leader J. F. Narramore, and Corporal D. W. Roberts (see page 99).

PLATE IV—MAJOR K. G. GROVES WITH DR R. J. MURGATROYD, WINNER OF THE PRIZE FOR METEOROLOGY

(See page 99.)

To face page 87

PLATE V—MAJOR K. G. GROVES AND AIR CHIEF MARSHAL SIR ANTHONY HEWARD WITH MR J. M. NICHOLLS, WINNER OF THE METEOROLOGICAL OBSERVER'S AWARD
(See page 100.)

PLATE VI—AWARDS TO CIVIL AIRLINE CAPTAINS AND NAVIGATORS
From left to right: Captain J. Vallance, Mrs J. Vallance, Director-General of the Meteorological Office, Mrs H. L. Chandor, Navigation Officer H. L. Chandor (see page 100).

Aircraft and instrumentation

At present we have two aircraft, a Canberra PR3 mainly for stratospheric research and a newly delivered Hercules—formerly a Lockheed C-130—primarily for research in the troposphere. Both aircraft have been substantially modified internally and externally, and much meteorological instrumentation has been fitted. This includes, on each aircraft, an advanced data-recording system by which samples can be obtained of up to 47 analogue and digital parameters at an overall sampling rate of 640 a second and recorded in 12-bit words on 1-inch magnetic tape. A PDP8/I computer located within the MRF building is used for transcribing the sequentially recorded airborne tape into a computer-compatible format. It is probably best to describe the aircraft one at a time.

Canberra WE 173 (Plate I)

This aircraft has a maximum endurance of about 3½ hours and a ceiling of about 15 kilometres. As well as a pilot and navigator it can carry an MRF scientist sitting alongside the navigator. His function is to monitor and occasionally to control the output of the meteorological sensors as it is fed into the data-recording system. The major modification to the aircraft is the construction of a 15-ft nose probe so as to expose instruments sufficiently far ahead of the aircraft as to be in undisturbed air. A pitot and static-pressure system is carried at the tip of the boom together with wind vanes to determine angle of attack and angle of side-slip. Outputs from these vanes and the pitot–static system, used in conjunction with a stable platform—an ancient Ferranti FSP 100—enable us to determine horizontal and vertical gustiness.

Other major instrumentation of this aircraft consists of:

(a) *A sub-millimetric interferometer.* This instrument, developed by the National Physical Laboratory (NPL), covers the region from 8 to 40 cm^{-1} in which occur emission lines from several of the stratospheric trace gases. Although it is primarily intended for the measurement of high-level water vapour, estimates can also be obtained of the concentration of oxygen, ozone and the oxides of nitrogen. This equipment has only recently been brought into operational use and very few flights have been achieved so far.

(b) *A downward-facing radiometer.* This is a modified version of the Oxford University multi-channel radiometer currently being flown in the NIMBUS E satellite. The 12 channels employed in our version cover the wavelength interval from 3 μm to 50 μm in discrete intervals and also from 100 μm upwards and are used if possible in conjunction with satellite transits nearby.

(c) *An upward-facing radiometer.* This too is an instrument designed and constructed by the Department of Atmospheric Physics at the Clarendon Laboratory, Oxford. The instrument has three channels which measure radiation in the infra-red at about 12 μm, 50 μm and 100 μm respectively. Both these radiometers have been extensively test-flown and are now in operational use.

Other instrumentation in the Canberra includes a Rosemount thermometer, a manually operated Dobson–Brewer hygrometer and exposable filters for sampling particulates at high level, as well as the normal range of standard aircraft instruments.

Hercules XV 208 (Plate II)

This aircraft was delivered to us in January 1974, having been extensively modified since 1971 by Marshall's of Cambridge for its meteorological role. It has a ceiling of about 11 kilometres and a maximum endurance of more than 12 hours. It also has the ability to operate at low levels—below 150 metres, occasionally 30 metres over the sea—for more than 9 hours.

The major modifications consisted of:

(a) *The nose-boom.* A 22-ft nose-boom was constructed on which to expose pressure and temperature sensors together with pairs of wind vanes. The boom was built as an integral part of the aircraft to a rigorous specification of stiffness, and has a natural resonant frequency of about 15 Hz. At the base of the boom is housed a Ferranti stable platform with outputs to the navigator and to the data-recording system.

(b) *The repositioning of the radar.* In a basic C-130 aircraft the precipitation radar is located in the nose. Our nose-boom requires the radar to be located elsewhere, and consequently it has been sited in a pod situated near the centre line of the aircraft directly above the aircrew cabin.

(c) *A drop-sonde ejector.* One of the research projects at present being conducted by the C.P.B. involves the use of a drop-sonde. A suitable mechanism for ejecting these sondes has been designed and installed in the upper 'clam-shell' door at the rear of the aircraft. The design of the sonde and its ejection velocity are both critical in ensuring that it shall miss the aircraft tail after ejection. The aircraft is also fitted with a large storage area for up to 70 sondes of the type envisaged, namely a right circular cylinder about 110 cm long and 13 cm in diameter.

(d) *A recorder van.* The fuselage of a standard C-130 is very noisy—up to 115 decibels* in places—and is not conducive to lengthy periods of scientific endeavour. Rather than attempt to sound-proof the entire fuselage, it was decided to construct a transportable cabin or caravan, which would normally be anchored to the floor of the aircraft but which could be removed by fitting to it a set of wheels. The van has 10-cm thick glass-fibre walls enclosed in continuous metal sheets, and this construction renders the interior acoustically and electrically quiet. The van, roughly 4 m × 2 m × 2 m houses the data-recording system—essentially a precision tape recorder—and all the monitoring and control points of the meteorological sensors together with up to four scientists.

In the two front positions are situated the controls for the data-recording system, the Decca Navigator, the E290 radar—control of which can be passed by the navigator to the MRF scientists who can then program the elevation scan of the antenna; the radar output on a slave display in the van is photographed at 1-second intervals—and also controls for the opening and closing of the door for the downward-facing camera. In the front section of the van there are two television monitors which are linked to a pair of forward-facing TV cameras in the nose of the aircraft which provide the occupants of the van with a view of about 120° ahead of the aircraft.

*This noise level is measured relative to the conventional threshold value for the lowest level of audibility of 2×10^{-5} Pa.

The rear section of the van is separated by racking which extends across the centre of the van. This racking houses the data-recording system, the basic power packs, and a variety of displays and controls operated by the scientist seated at the back. The displays include digital indicators and also several paper-chart recorders which permit the continuous presentation of a selection of variables, e.g. air temperature, dew-point and sea surface temperature. The controls include the operation and calibration of the downward-facing radiometer, a Barnes ART4, which measures upwelling radiation in the 'window' region from 8 to 12 μm. The van is fitted with its own air-conditioning unit, originally designed for operation only on the ground, but soon to be modified to allow complete independence from the circulation system of the aircraft.

(e) *An air-sampling boom.* It is desirable to have a facility by which instruments can be exposed in flight and then be withdrawn into the cabin. For an aircraft with a pressurized fuselage it is necessary to design a scheme which will preserve the seals as far as possible and still allow some degree of flexibility in the type of instrument exposed. Our boom has been used for developing instruments and also on flights where a change of sampling-head—or of a particular part of the head—is necessary.

So much for the major conceptual and constructional changes which have been effected on the aircraft. Since the delivery of the aircraft in January 1974, most of our effort has been directed towards providing and testing suitable meteorological sensors. These include:

(a) Wind vanes mounted near the tip of the nose-boom to measure angles of attack and side-slip. Their deflexions can be measured with an accuracy of about 1·5 minutes of arc and can be recorded at a frequency of 40 a second.

(b) Rosemount thermometers which are also mounted on the nose-boom. Sensitive to about 0·1 deg, these too are recorded 40 times a second.

(c) A stable platform, a Ferranti Miniature Platform type B, is installed in the base of the boom. As with the Canberra, outputs from the platform can be combined with the vane data to give components of gustiness.

(d) A forward-facing 16-mm Telford camera, mounted on the cabin window between the first and second pilots. Operation of this camera is controlled from the van.

(e) An air-sampling pipe, 5 cm in diameter, which draws air into the fuselage and then, after a 1·2-m traverse, vents it out again. This pipe can be used for chemical sampling.

(f) Three independent instruments for the measurement of humidity. These are a Dobson–Brewer manual hygrometer, a Cambridge Systems automatic hygrometer—both of which measure frost-points—and a radio refractometer. This latter is mounted temporarily on an extensible boom.

(g) The boom has also been used to expose a Johnson–Williams liquid-water-content meter, and various types of carriers of filter papers from which samples of sulphates and SO_2 or freezing nuclei can be obtained.

(h) A downward-facing 35-mm Vinten camera, operated from the van.

(j) The downward-facing Barnes ART4 radiometer already mentioned.

As well as the above, arrangements are in hand for the mounting of a Knollenberg droplet spectrometer on one of the aircraft windows, and also the installation of an area for the testing, calibration, and signal-reception of drop-sondes.

Because of the difficulties encountered in the removal of sensing heads from the skin of a pressurized aircraft, it has been decided that major installations of equipment will take place in pods mounted below the wings. Three suitable pods—they are in fact jettisonable fuel tanks—and mounting pylons have been purchased and the wings have been suitably strengthened to take the extra load. The first of these pods will house a laser disdrometer, currently undergoing development in the C.P.B., which will make it possible to obtain holograms of cloud particles at a rate of one a second when necessary. A laboratory designed specifically to receive the pod and its laser has been constructed at the MRF building.

The research program

The research of the MRF is, of course, carried out under the general guidance of the Meteorological Research Committee (MRC). Annually a research program is prepared by the Chief Meteorological Officer, MRF for the forthcoming year, based on these recommendations, and approved by the Director of Research. As has been mentioned earlier, because of staff limitations, the actual scope of the research projects instigated within MRF is small, and largely confined to atmospheric dynamics; most of our flying, particularly with the Hercules, is on behalf of other branches of the Meteorological Office, especially the C.P.B., and for other national and international meteorological agencies.

The first part of the MRC program of research is concerned with instrumentation, and this occupies a large proportion of our effort. Most of this work has been mentioned in earlier sections above and will not be dealt with separately. The second and third parts of the MRC program deal with dynamical and physical investigations, but it is perhaps easier to define our physical-research projects with respect to the aircraft involved.

Physical research

(1) *Canberra*

(a) *Stratospheric composition.* The interferometer installed in this aircraft can give information about mixing ratios of various trace gases in the stratosphere. These include water vapour, ozone, and the oxides of nitrogen; ozone and water vapour are also measured directly by means of a Brewer Bubbler and a Dobson–Brewer manual frost-point hygrometer respectively. Our aim is to ascertain these mixing ratios on a regular basis and in a variety of meteorological situations in order to establish their mean values and variations therefrom. It is also possible—by banking the aircraft slightly—to obtain some information from the interferometer about the vertical variability of water vapour and ozone. This is an MRF-instigated project but of course follows on from, and is still closely related to, the work at the NPL.

(b) *Radiation from cirrus cloud.* The purpose of this project is to investigate the radiative properties of cirrus cloud in a number of discrete wavelength intervals in the hope of formulating techniques by which some of the properties of the clouds can be determined by remote sensing. The upward-facing radiometer has only three channels, which are at about 100 μm, 50 μm and 12 μm, but the downward-facing radiometer has many more channels in addition to

these three. One of the channels included is at about 3 μm, where absorption due to water vapour and CO_2 is strong, and is intended to measure solar radiation reflected from cirrus tops. The radiative properties of cirrus differ widely at the wavelengths chosen, and it is hoped that the differences can be related to number-density and to particle size. This project is controlled by the Department of Atmospheric Physics at the Clarendon Laboratory in Oxford.

(c) *The transparency of 'window' regions.* Considerable uncertainty exists at present concerning the transparency of the atmospheric 'windows' at 11 μm and 3·5 μm commonly used for the determination of sea surface temperatures from satellites. Indeed there is a significant discrepancy between the true and the derived equivalent black-body temperature. Much of this, it is thought, is due to the non-transparency of the 'windows', with the water-vapour dimer* playing an important role at 11 μm. Several channels are available in the downward-facing radiometer for the examination of the wavelength dependence of the dimer absorption. This project, too, is controlled by the group at Oxford. Recently the aircraft was detached to Dakar, Senegal in order to extend to tropical regions the above two projects.

(d) *Collection of atomic debris.* The Health Physics Division of the Atomic Energy Research Establishment at Harwell are interested in obtaining samples of any debris from atomic explosions which may be present near the tropopause. No special flights are arranged, but filters are exposed—usually one just below and one just above the tropopause—on an opportunity basis when another project calls for flights at these levels.

(2) *Hercules*

(a) *The structure of fronts (Project Scillonia).* The purpose of this project is the investigation of the distribution and intensity of frontal—and in particular warm-frontal—rainfall, and it involves the detailed three-dimensional analysis of a section of an active front both over the sea and over land. The project began in 1968 with experiments involving Doppler radars, the Varsity aircraft of MRF, and drop-sondes, and was located near the Isles of Scilly. This phase was completed in 1971, and subsequent analysis of the data was sufficiently encouraging to justify a second series of more ambitious experiments. In the interval since then, the Hercules has replaced the Varsity and the C.P.B., who control the project, have been developing a new drop-sonde with which to replace the self-opening radar targets which were dropped from the Varsity. The new sonde will incorporate the LOCATE system of positioning—and hence wind-finding—based on the LORAN-C navigation network, and will transmit its information to the aircraft for processing and recording. In this way, the project is made independent of ground-based radars (for sonde-tracking) and the full potential of the aircraft—its range, ceiling and precipitation radar—can be used to locate an active part of a front well away from land.

(b) *Orographic enhancement of rainfall.* The Meteorological Research Unit, a part of the C.P.B., which is located at the Royal Radar Establishment (RRE) at Malvern, is concerned with the use of radar in meteorological research. One of its projects is the investigation of the influence of the Welsh hills on the enhancement of rainfall in frontal situations. Early in 1975 they established a radar in west Dyfed to work on this project in conjunction with similar radars at

* Dimer: molecular species formed by union of two like molecules.

Defford. Our aircraft, the Varsity and Hercules, were used on suitable occasions to make vertical soundings near each of the two radar positions to measure the physical and dynamical properties of the cloud and its environment.

(c) *Convective cloud.* Before its disposal in April 1975, the Varsity aircraft, fitted with a field mill, conductivity probes and a cloud-droplet-charge detector, had carried out an investigation of the electrical properties of developing cumulus clouds. The data gathered in the course of this study are being examined by the C.P.B., who designed the instrumentation, and it is expected that similar instrumentation will be made for the Hercules. Even so, other parameters of cumulus clouds are to be investigated, in particular the number-density, size, composition and variability of cloud particulates, using both the Knollenberg disdrometer and laser holography.

(d) *The distribution of freezing nuclei in the atmosphere.* Some years ago a technique was developed by the C.P.B. for the determination of the number of freezing nuclei near the ground. This involved passing a known volume of air through a fine filter and then, by adjusting the temperature and degree of supersaturation in the chamber, allowing ice crystals to grow. They could then be counted with a microscope. A similar technique is being tried on the Hercules and first indications are that the modified method is successful. The program envisaged involves obtaining the vertical distribution of the nuclei on a regular basis and in a variety of meteorological situations.

(e) *The distribution of fluorocarbons in the atmosphere.* A simple scheme has been devised which makes it possible for samples of the outside air to be obtained, via the sampling pipe, in sealed containers the contents of which can then be analysed on the ground. The C.P.B., in conjunction with the Health Physics Division at Harwell, are co-operating in the determination of the fluorocarbon content of these samples.

(f) *Long-range transport of SO_2 in the atmosphere.* For the past few years we have been conducting flights, at first by the Varsity and later by the Hercules, over the North Sea in order to determine the amount of SO_2 being put into the atmosphere by the industrial areas of the United Kingdom and also the residual amount reaching the coast of Norway. The technique used consists of drawing a known volume of air through a series of filters which remove sulphates and SO_2 separately. (The source and trajectory of the air being known, an estimate of conversion rate can be obtained.) A sample is obtained every 20 minutes or so, and the flying is restricted to low levels and to those occasions when a broad south-westerly flow is limited by a good cloud-free inversion. Papers have been written on the instrumentation and the results by members of MRF, the Boundary Layer Branch of the Meteorological Office, and the Health Physics Division at Harwell (Aanensen and Grant, 1966; Johnson and Atkins, 1974 and 1975; Smith and Jeffrey, 1975).

(g) *Sea surface temperatures.* The ability of the Barnes radiometer to determine sea surface temperatures with sufficient accuracy—particularly relative accuracy—to be of use in oceanographic studies was demonstrated by Dr (now Professor) J. D. Woods in his experiments near Malta. More recently, the aircraft—at first the Varsity and then the Hercules—have made some measurements of sea surface temperatures for the Department of Oceanography of the

University College of North Wales, Bangor. These flights, always at low levels in order to minimize the correction for water vapour, have been confined to the Irish Sea, and were in association with ship observations being made at the same time. It should also be mentioned that extensive use was made of this facility in the recent GATE (GARP Atlantic Tropical Experiment) Project, in particular in the final phase of the experiment which was largely devoted to oceanographical observations.

(h) *Solar radiation.* In association with the Observational Requirements and Practices Branch, a program to measure the attenuation of solar radiation by clouds and the atmosphere has been prepared. We are, as yet, only in the early stages, namely obtaining and installing appropriate instrumentation.

Dynamical research

(a) *Mountain-induced momentum fluxes.* Since 1973 measurements have been made of the vertical flux of horizontal momentum ($\overline{\rho u' w'}$, where ρ is density and u' and w' are the perturbation horizontal and vertical components of air velocity respectively) in stably stratified flows over mountains. As in clear-air turbulence work, u' and w' are obtained at 20 Hz from the full gust equations (see Axford, 1968), which require inputs of the incidence of the airflow to the aircraft (measured by the angle-of-attack and side-slip vanes), the component of air velocity relative to and along the aircraft's longitudinal axis (measured by the experimental pitot–static system) and the altitude and velocity of the aircraft with respect to the ground (measured by instruments located in the inertial platform).

Twenty flights have been made over the Colorado Rockies in a collaborative project with the National Center for Atmospheric Research (NCAR), with the MRF Canberra operating in the stratosphere and one or two NCAR aircraft concurrently covering altitudes from the surface to the tropopause. Additionally about 10 flights have been made by the Canberra alone at heights of between 10 and 15 kilometres over the mountains of the United Kingdom, and three flights have been made by the Hercules in the troposphere over the mountains in Scandinavia. In all future flights on this MRF project it is planned to operate two MRF aircraft together to give good vertical resolution and coverage up to the lower stratosphere.

The purpose of the flights is to obtain quantitative estimates of the vertical-flux profiles in a variety of synoptic situations and over a variety of mountain ranges. Observed quantities can then be used as a check of the predictions of various theoretical models of mountain flow and induced fluxes (being developed mainly in the U.S.A.). If these models are satisfactory they can (if necessary) be incorporated in numerical global-circulation models. Lilly (1972) has shown for example that a downward flux of about 10^{-4} N/cm^2 (which would occur on about 10–20 occasions a year over the Rockies) below jet-stream level could cause an overestimation by about 15 per cent of the jet-stream speed, if not incorporated in numerical prediction models.

A secondary aim of these flights is to obtain measurements of fluxes and energy budgets (with an enhanced vertical resolution) near critical layers, the most easily identifiable of these being a zone of wind reversal above standing waves. Such layers, however, rarely occur within the height range of the Canberra.

On the flights made so far, several interesting flow patterns have been encountered, some being associated with moderate to severe turbulence and with difficulty in the handling of the aircraft. Figure 1 shows streamlines of airflow (as represented by isentropes) and horizontal wind speeds at Canberra flight levels on 18 January 1973 over the Rocky Mountains, and Figures 2 and 3 show the wind speed and temperature changes at a height of 10·9 km associated with the disturbance of double amplitude 1·2 km immediately over the highest peak. Fluctuations of about 90 kn (46 m/s) in the horizontal wind component, 20 kn (10 m/s) in the vertical component, and 13 deg in temperature, occurred in this disturbance. Patterns of flow which are similar to that shown in Figure 1, but of lesser amplitude (about 0·5 km) have been found over the Welsh mountains at 10·9 km.

(b) *Clear-air turbulence (CAT).* After an intensive period of clear-air turbulence research, culminating in the profitable collaborative work (see Browning *et alii*, 1973) with the MRU at RRE, Malvern in 1972 (which established that breaking Kelvin–Helmholtz waves were a source of clear-air turbulence experienced by an aircraft), there has been a lull in the MRF CAT research program. This was induced both by intensive effort on other high-level dynamical work (as in (a) above), and a lack of definition of *obvious* further fruitful avenues of investigation of the environment and formation of turbulence which can be followed up by a gust-research aircraft.

The current MRF program of research on turbulence is aimed at comparing turbulence spectra at sea away from gravity-wave input with those over land from the same portion of the jet stream, as well as assessing gravity-wave energy below and above turbulent zones over land; in other words it is directed at establishing whether gravity waves merely act as a trigger to CAT in shear zones below jet streams, or whether they supply energy as well.

A by-product of these flights would also be the securing of better data on the volume of atmosphere which is breaking down into turbulence in jet streams, since the flight plans (for the Hercules) include runs some 1100 km in length along the shear zone beneath the jet as well as frequent profiling sections across it. Estimates of the mean turbulent energy dissipation over a volume of atmosphere of synoptic dimensions are of importance in determining whether such effects should be included in forecasting models. Such estimates will also require better information on the volume of atmosphere filled by an individual group of Kelvin–Helmholtz waves and, as a separate exercise, we also hope to make flights to examine energy budgets and dimensions of individual wave groups on days when the waves are producing billow clouds. This work would be done by the Hercules only, but the gravity-wave work referred to earlier would involve both aircraft.

(c) *Low-level flow patterns near mountains.* A few low-level phenomena exist over the United Kingdom in stably stratified flows over mountains in which we have no or few measurements; two examples are the rare destructive surface winds to the lee of the Pennines and the associated lower tropospheric flow field, and rotor-streaming beneath a low-level reversal of wind (which may be another case of a critical-layer effect). Hercules flights will be made to investigate these phenomena when they occur—this too is an MRF project.

(d) *Fluxes near stratocumulus cloud.* Measurements of gross atmospheric conditions, and of the fluxes of heat, water vapour and momentum are being

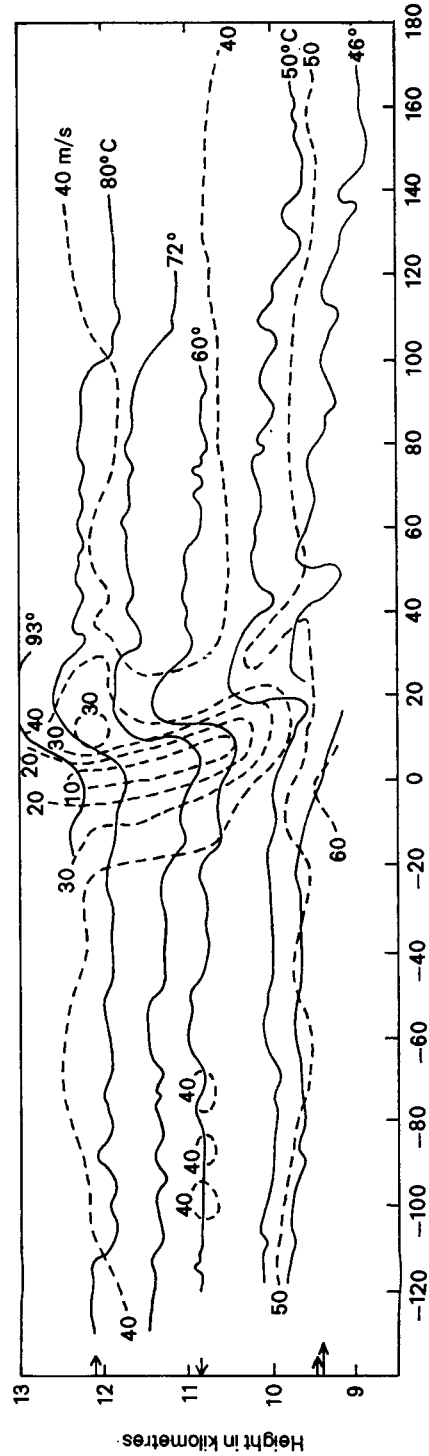

FIGURE 1—THE WIND AND POTENTIAL-TEMPERATURE FIELD MEASURED BY THE CANBERRA AIRCRAFT ABOVE THE COLORADO ROCKIES ON 18 JANUARY 1973

——— Potential temperature - - - - Westerly wind component

Arrows on the height axis indicate flight levels. The terrain beneath the flight pattern is rugged, with several peaks over 4 km from −120 to 0 km, after which it falls away to a 1·6-km plain beyond 20 km. The potential-temperature lines approximate to streamlines of airflow on this flight. 1 m/s ≈ 2 kn.

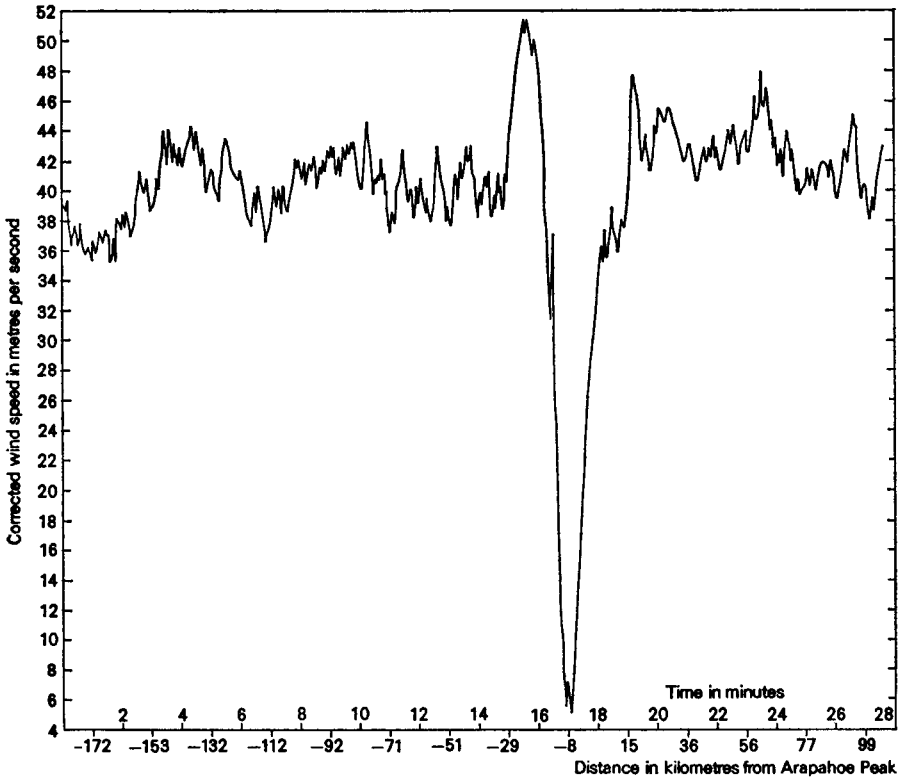

FIGURE 2(a)—HORIZONTAL WIND-VELOCITY COMPONENT FOR A RUN AT A HEIGHT OF 10·9 KILOMETRES

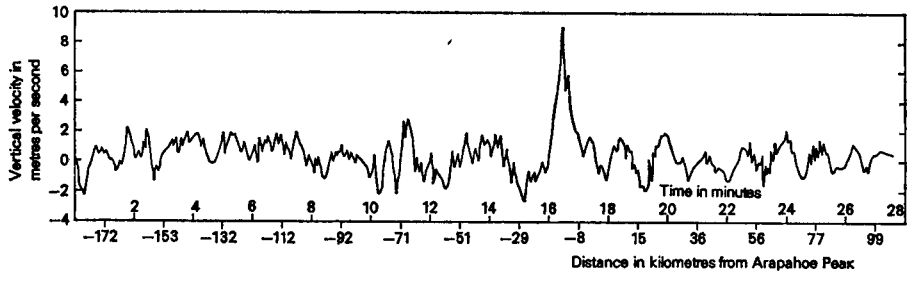

FIGURE 2(b)—VERTICAL WIND-VELOCITY COMPONENT FOR A RUN AT A HEIGHT OF 10·9 KILOMETRES

made above and beneath decks of stratocumulus cloud with the Hercules aircraft on this MRF project. Temperature and humidity perturbations used in the flux calculations are derived from a rapid-response platinum resistance thermometer and a refractometer respectively. Measurements are being made with a vertical resolution of about 50 metres and a time resolution of about two hours. The aim of the flights is to relate cloud structure and cloud behaviour to the fluxes measured.

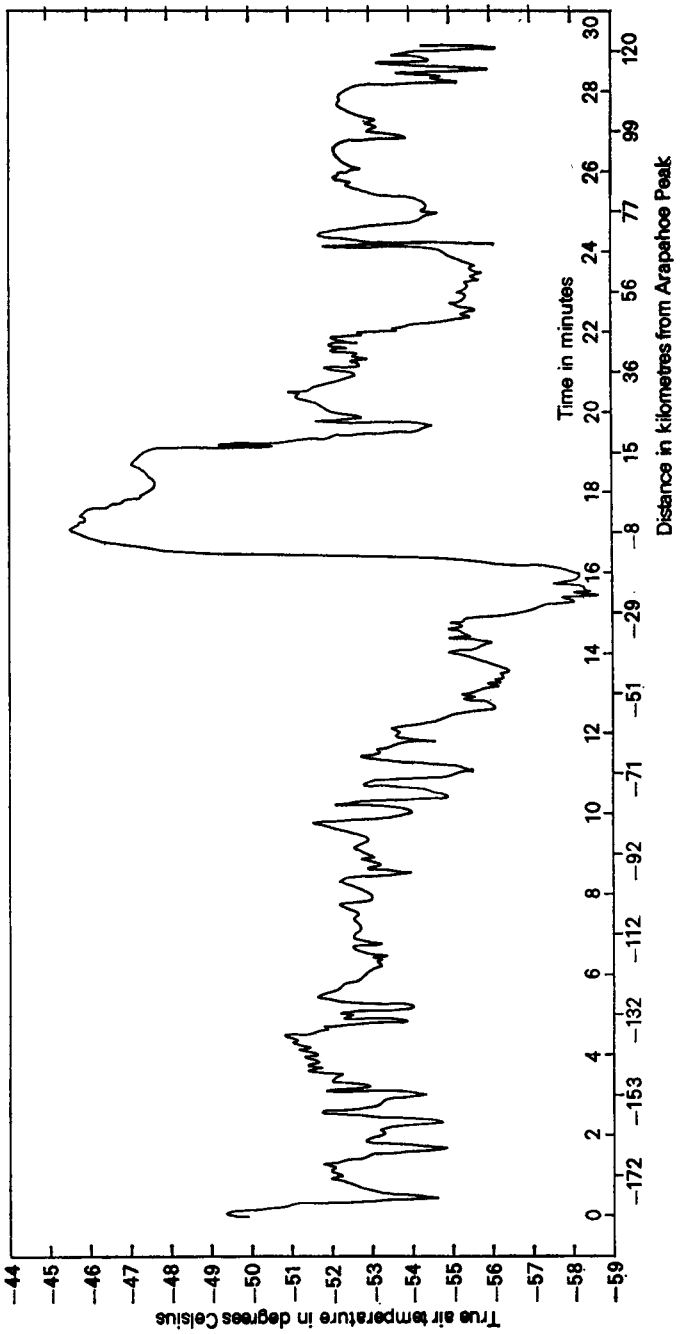

FIGURE 3—TEMPERATURE MEASURED ALONG THE RUN AT 10·9 KILOMETRES

(e) *Examination of the boundary layer over the sea.* The measurement of boundary-layer fluxes of heat, moisture and momentum over the tropical Atlantic formed the major part of the MRF contribution to the Global Atmospheric Research Programme Atlantic Tropical Experiment (GATE) in the summer of 1974. The Hercules was flown for over 350 hours at levels between 30 metres and 1600 metres on a variety of flight patterns in conditions ranging from completely calm and undisturbed (with low-level stability and no cloud) to extremely disturbed (under and in the base of tropical cumulonimbus clouds). Atmospheric convergence fields were also measured in areas of 6250 to 25 000 square kilometres in association with various cloud systems.

The measurement of boundary-layer fluxes over the sea continues to be a part of the MRF research program, the emphasis being placed on the measurement of the transfer of momentum from the atmospheric boundary layer to the sea in disturbed conditions (with wind speeds in excess of 30 kn (15 m/s), a situation in which ships cannot operate tethered balloons to make similar measurements. Several successful flights have already been made.

Conclusions

It is obvious from the foregoing account of the MRF research program that most of the work is aimed at fulfilling purely meteorological purposes. However, it is hoped that some of the research and of the data being gathered is of interest to other organizations, for example aircraft manufacturers, operators and certifiers; of particular interest may be the work on atmospheric pollution at stratospheric levels, high-level airflow over mountains, clear-air turbulence, and the composition of convective clouds (upon which icing criteria may depend). Two other points should be noted: firstly, data are recorded (but not analysed at MRF) in flight conditions which may be of direct interest to researchers in aeronautical sciences—for example, each landing produces a wind and temperature profile and low-level turbulence data on the magnetic tapes, and the profiles have good vertical resolution; secondly, it is hoped that all flight data will be available to any user, in the near future, in the form of computer-compatible tapes to be kept in the Archives of the Meteorological Office at Bracknell. Each tape will be documented and users could then perform any type of analysis that they desired on the flight data.

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AWARDS

L. G. Groves Memorial Prizes and Awards

The annual award of prizes took place on Friday 14 November 1975 at the Ministry of Defence, Whitehall. The Air Member for Supply and Organization, Air Chief Marshal Sir Anthony Heward, K.C.B., O.B.E., D.F.C., A.F.C., presided and the Prizes and Awards were presented by Major K. G. Groves, who was accompanied by Mrs Groves. The ceremony was attended by the Director-General of the Meteorological Office, Dr B. J. Mason, C.B., F.R.S. (See Plates III–V.)

The 1975 Aircraft Safety Prize was awarded to Squadron Leader J. F. Narramore, B.E.M., of Royal Air Force Laarbruch, with the following citation:

'With the advent of the axial-flow compressor in gas turbine aero engines, damage from foreign object ingestion has become a serious flight safety hazard, resulting in loss of life and the destruction of aircraft. It has been estimated that foreign object damage (FOD) now costs the Royal Air Force nearly twelve million pounds annually in aero-engine maintenance. In an attempt to reduce FOD at Royal Air Force station Laarbruch, Squadron Leader Narramore intensified the existing methods of FOD prevention, including research into the sources of foreign objects.

His initiation of a high-intensity airfield-sweeping programme produced good results, but he observed that the available sweepers did not adequately collect ferrous metal objects of the size and type known to cause most FOD. He therefore designed, and had built from available materials, a special electromagnetic sweeping machine; this has been a great success, as it is effective over both soft and hard surfaces and is particularly flexible and safe in use. It is now being considered for application throughout the Royal Air Force.

Squadron Leader Narramore's efforts have drastically reduced the extent of aero-engine FOD at Royal Air Force Laarbruch and he has clearly shown how this potential cause of accidents can be controlled in future. It is for this significant contribution to flight safety that he has been awarded the 1975 L. G. Groves Aircraft Safety Prize'.

The 1975 Meteorology Prize was awarded to Dr R. J. Murgatroyd, O.B.E., of the Meteorological Office, with the following citation:

'This prize is awarded to Dr Murgatroyd for his contributions to the study of the stratosphere, particularly in regard to the possibility of effects of supersonic aircraft on the ozone layer and climate. During the years 1972 to 1975, Dr Murgatroyd has led a team of investigators in the universities and government establishments and as a result of his efforts, a wide range of scientific expertise has been brought to bear on the complex problems of stratospheric dynamics

and photochemistry. Significant scientific advances have been made towards fuller understanding of phenomena as diverse as the sudden winter warming of the stratosphere and the photochemical balance of the ozone layer. In particular it has been demonstrated that the planned fleet of Concorde aircraft will have no significant effect on the climate or on the ozone layer.'

The Meteorological Observer's Award was awarded to Mr J. M. Nicholls, of the Meteorological Research Flight, with the following citation:

'This award is made to Mr Nicholls for his contributions to the observational programme of the Atlantic Tropical Experiment of the Global Atmospheric Research Programme (GATE) and more generally for his scientific exploitation of the observing capability of the Meteorological Research Flight. Mr Nicholls' efforts played a very large part in ensuring that the newly acquired Hercules aircraft was instrumented effectively and ready in time for this international (GATE) programme in which it played a key role. Mr Nicholls took part in a number of the long flights conducted during the experiment and played an active part in the international planning and co-ordination of the aircraft programme. In this respect his scientific insight was very important in ensuring an effective international programme appropriate to the scientific problems.'

The Second Memorial Award for 1975 was awarded to Corporal D. W. Roberts of Royal Air Force Ternhill, with the following citation:

'Gnome engine stall and rundown in RAF helicopters has long been a flight safety hazard, particularly in the single-engine Whirlwind, and has been the cause of a number of accidents. Over the last three years, Corporal Roberts has completed much valuable work that has resulted in an improved understanding of the cause of these engine failures and has led to the introduction of preventive measures. His latest investigations have produced more valuable information to help with achieving an ultimate understanding of this complex problem.

The efforts of Corporal Roberts are particularly commendable because, as a clerk statistics, he is not an engineering tradesman, yet he has completed outstanding work towards improving the integrity of the Gnome engine. For this significant contribution to flight safety he has been awarded the L. G. Groves Second Memorial Award.'

Meteorological Office awards to captains and navigators of civil airlines

Since 1954 the Director-General has made awards annually to encourage civil airline captains and navigators in making and transmitting airborne weather reports. Suitably inscribed books are awarded to aircrew members who have provided the best series of reports during the year. In addition captains who have given long and meritorious service in the provision of reports are considered for the award of brief-cases.

At a ceremony on 1 October 1975 at the Meteorological Office Headquarters the Director-General presented brief-cases to Captain J. Vallance, British Airways (Overseas Division) and to Navigation Officer H. L. Chandor, British Caledonian Airways (see Plate VI). This is the first time that a navigator has received the award of a brief-case, but because of the excellence of his reports over a long period it was decided, exceptionally, to make one of the awards to Mr Chandor.

REVIEWS

Methods in agricultural meteorology. Developments in atmospheric sciences, Volume 3, by L. P. Smith. 250 mm × 170 mm, pp. xii + 21, *illus.*, Elsevier Scientific Publishing Co., Amsterdam and New York, 1975. Price: Dfl. 75.

Even had this book been published anonymously, and without the very characteristic portrait which adorns the frontispiece, no one familiar with the style, approach and strong convictions of L. P. Smith could have the slightest doubt as to its provenance. Solidly down to earth but rarely if ever dull, often illuminating the subject with passing comments of deep insight, the author peppers his text with relevant quotations from world literature and shows himself a master of the graphic phrase which can make a diagram superfluous. (For example, the statement on page 68 that the shape of a particular graph 'resembles the track of a somewhat lofted drive at golf against a headwind'.).

The opening chapters are concerned respectively with the scope of agricultural meteorology and with the input data which are available on the meteorological and biological sides. Warnings of the imperfections and limitations of simple or derived weather parameters will be particularly useful to non-meteorologists. The next two chapters deal in turn with crops and farm animals in health and sickness; the sections here on plant and animal diseases are among the best in the book. Chapter 5 on soils, fertilizers and mulches is less impressive, largely perhaps because the complex processes involved have been difficult to quantify. Chapters 6 and 7 deal briefly but competently with such topics as irrigation, shelter, farm housing, storage and transport; and with weather forecasts for agriculture, and problems of frost and other meteorological hazards. The last chapter is made up of practical and helpful advice on how best the agrometeorologist might present his findings to different audiences in written or spoken form. Here the accumulated wisdom of a quarter century of communications experience—articles, books, public platforms, radio and television—has been distilled in a form which cannot but benefit young people and not only those in the field of agricultural meteorology.

There are two appendices. The first is an annotated list of the studies of agrometeorological subjects which have been published as WMO *Technical Notes*. This invaluable series has not yet received the attention it deserves outside meteorological circles and it was an excellent idea to afford it wider publicity. The second appendix is a catalogue of annotated bibliographies issued by the Commonwealth Agricultural Bureaux.

The content of the final appendix draws attention to the fact that the book, despite the generality of its title and that of the series in which it appears, is in fact virtually confined to British methods and experience, and is predominantly based on the work of the stalwart triumvirate of L. P. Smith, W. H. Hogg and R. W. Gloyne, with the backing mainly of G. W. Hurst, C. V. Smith and (honour to a non-meteorologist!) C. B. Ollerenshaw. At its best, the book draws strength from this in-breeding. Details are given of the pragmatic British approach to agrometeorological problems, aimed at developing practical rules of thumb which can be used to give operational advice to farmers. Timid students of agricultural meteorology will be encouraged by this forceful approach and

indeed by Mr Smith's caveat against unbecoming modesty caused by lack of knowledge: 'rest assured that other people probably know considerably less' (p. 148). Academic theorists may blanch in the face of what they may feel to be the wildly speculative models which are adopted in drawing up daily balance sheets of soil moisture (pp. 50–54) and elsewhere; the author's justification would be that the end results in practical application justify the apparently dubious means.

There is what appears to be a cry from the soul in the last sentence of the text, which advises potential writers of books: 'Don't . . . the writing of a book is sheer undiluted hard work'. Here and there throughout the present work there are hints of impatience in the writing. Sometimes it takes the form of an imprecision of language which is quite uncharacteristic of the author; e.g., (p. 50) 'it may be necessary to know the moisture content of the topmost layer of soil which contains the first 10 mm of soil moisture'. On rare occasions the author's vigorous style topples over into the intemperate. At a time when architects are belatedly discovering the help which meteorology can give them it seems indiscreet to accuse them of being 'scientifically illiterate' (p. 110). And in a book of predominantly British orientation it is surely a little unfair to dismiss grass-minimum temperature readings out of hand because grass does not grow freely in many parts of the world (p. 28). Some repetition is virtually unavoidable in a text of this kind but in places it seems excessive. Detail of little or no relevance, e.g. the list of areas not covered by artificial insemination centres in England and Wales (p. 100), might well have been pruned.

These minor criticisms of the book do not in any way dim one's satisfaction that, not for the first time, Mr. Smith has disregarded his own advice. At a time when the older generation of workers in this field are bowing out from the stage, he has poured the quintessence of his long experience into an excellent operational textbook which will be a valuable guide and source of inspiration to young agrometeorological students. Few experienced colleagues would disagree with his major theses, although some might wish to suspend judgement on particular techniques. The present reviewer takes serious exception only to one conclusion. The author refers to a reminiscence by Hilaire Belloc of a youthful indiscretion; the fact that the old man, all passion spent, was able to recall the wine but not the girl is curiously put forward by Mr Smith as a telling example of a correct sense of priorities. Luckily it is a case where the young student can confidently be relied upon to reach his own conclusions.

P. M. AUSTIN BOURKE

Readings on the climate of West Malaysia and Singapore, edited by Ooi Jin Bee and Chia Lin Sien. 255 mm × 195 mm, pp. x + 262, *illus.*, Oxford University Press, Oxford Books, 37 Dover Street, London W1X 4AH, 1974. Price: £10.

This collection of 19 published papers has been made for specialist and general readers variously concerned with the preservation of the environment and with services to the community. Publication dates range from 1954 to 1972 but two-thirds are post-1962.

The first of a set of four papers on synoptic meteorological topics is the well-known set of meticulously documented accounts of line-squalls (of airstream

boundary and Sumatra types) by I. E. M. Watts. The others are on north-east monsoon rainfall. K. Bryant's study of a wet December and a dry January at Singapore is followed by two papers by Gan Tong Liang. One examines large falls on the east coast of Malaya and derives three rules for forecasters. The second contains as Fig. 4.3c, a streamline analysis, at the 700-mb surface showing a large, anticlockwise circulation centred at the equator and labelled as a cyclonic vortex. Many analysts will object to this.

Of four papers of traditional climatology, two deal with sunshine and radiation, presenting many useful statistics, one summarizes temperature and humidity data and a short but interesting paper deals with Singapore's diurnal and seasonal cloudiness. Next come four papers on rainfall. I. E. M. Watts presents a mine of useful information on Singapore, excellently illustrated. Fourteen case studies contain series of half-hourly isohyetal maps and relevant upper-wind data. W. L. Dale has two papers on the rainfall of Malaya, ably exploiting the available data to help many potential users including forecasters. C. S. Ramage, on diurnal variation of rainfall, packs much valuable information into a few pages. This paper should be followed by a longer one using satellite data.

Writing on probable maximum 24-hour precipitation, J. G. Lockwood obtains estimates of 1000- and even 10 000-year falls from mainly short records; the latter are surprisingly lower than his probable maximum estimates and his use of hurricane depth–area relationships for Malayan rainfall is at least questionable. The Singapore floods of December 1969 are graphically described by Chia Lin Sien and Chang Kin Loon, but without any synoptic charts. S. Nieuwolt's study of evaporation and water balances is most interesting, but lacks Penman calculations. P. M. Stephenson's index of comfort should help those planning projects in Singapore, and Nieuwolt's short discussions on the city's micro-climate should have many useful applications.

M. Mansell-Moullin ably exploits scanty data to obtain probable maximum storm and flood estimates and an informative water balance and utilization paper rounds off the collection on a practical note.

The compilers have collected up and augmented the sets of references alphabetically and have numbered all figures and tables as one set. There are a few misprints. The periods of rainfall averages are important and should have been more clearly indicated and a year-by-year study of north-east monsoons would have strengthened the work. Several of the rainfall studies could now be updated to include many more station-years of data.

Meteorologists, hydrologists, civil engineers, agriculturists and many other professional people working in the region and in low latitudes elsewhere should find the collection a useful acquisition.

B. G. WALES-SMITH

PUBLICATIONS RECEIVED

The following have been received from the Meteorological Institute of the University of Thessaloniki:

Climatologika 6: *Air temperatures at the Larissa Institute for Forage Cultivations.* By G. Banoutsous and V. Semerdjidis. 1974.

Climatologika 7: *Programs for the processing of wind data by computers.* By Charalambos S. Sahsamanoglou. 1975.

Meteorologika 44: *Statistical processing of air temperature data from the city of Athens for the period* 1946–1973. By Angeliki Arseni-Papadimitriou. 1974.

Meteorologika 45: *Total ozone and temperature variations in the lower stratosphere and related teleconnections in the Mediterranean area.* By Christos Zerefos and Antony Bloutsos. 1974.

Université de Thessaloniki. Annuaire de l'Institut Météorologique et Climatologique, 43. Observations Météorologiques de Thessaloniki 1974, publiées par le Prof. Dr. G. C. Livadas, Thessaloniki, 1975.

HONOUR

The following honour was announced in the New Year's Honours List, 1976:

B.E.M.

Mr D. McC. McSween, Chief Cook, Ocean Weather Ship Base, Greenock.

THE METEOROLOGICAL MAGAZINE

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked 'For Meteorological Magazine'.

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COMPARISON OF 50-MILLIBAR GEOPOTENTIALS DERIVED FROM SATELLITE INFRA-RED SPECTROMETER READINGS WITH THOSE DERIVED FROM A SERIES OF ANALYSED CHARTS

By N. R. WATSON and V. BAILEY

SUMMARY

Over the period from June 1974 to May 1975 comparisons were made of 50-mb geopotentials estimated (a) from an analysed chart series and (b) from SIRS data.

Two Vertical Temperature Profile Radiometers (VTPRs) were mounted on each satellite, and ground-controlled switching made it possible for them to be selectively interrogated. It was found that differences between the two estimates (a) and (b) showed marked discontinuities when the alternative VTPRs were switched in, and it was also found that for any one VTPR there was a marked latitudinal variation. The differences showed a marked decrease after the introduction of a new method of SIRS temperature retrieval in March 1975.

INTRODUCTION

During recent years, soundings of the vertical temperature profile of the atmosphere deduced from measurements made by radiometers mounted on satellites have become available. In particular the radiances measured by the Vertical Temperature Profile Radiometers (VTPRs) on board the NOAA series of spacecraft are used to produce the Satellite Infra-red Spectrometer (SIRS) soundings which are distributed on the Global Telecommunication System (McMillin *et alii*, 1973).

This paper reports some results obtained from a comparison of the 50-mb geopotentials obtained from SIRS soundings with those from a chart series, which used radiosonde data only, prepared by the Stratospheric Analysis Group in the High Atmosphere Branch of the Meteorological Office.

METHODS OF COMPARISON

Since April 1974 the Stratospheric Analysis Group have been drawing daily hemispheric 00 GMT charts of the 50-mb geopotential field, using radiosonde data only. The ascents are corrected for known differences between sonde systems, and great emphasis is placed on the continuity of flow patterns in order to produce a series of charts which represent the best available analyses.

The radiosonde network is mainly over land, with occasional island stations or weather ships in the oceanic areas. The SIRS soundings, however, are always made over the sea, and because NOAA spacecraft are in sun-synchronous orbits, the soundings made over a given area occur at approximately the same time every day. Any comparison between 50-mb SIRS and 'sonde' geopotentials must be made near 00 GMT each day in order to minimize the effect of any large-scale changes in the pressure field. Therefore only SIRS soundings within three hours of 00 GMT were used in the comparisons, and this meant that the comparison areas were restricted to the Atlantic and to the western Pacific off Japan.

The SIRS soundings are received as the geopotentials of the standard levels relative to the 1000-mb surface. The 1000–50-mb thicknesses were therefore plotted on the appropriate 00 GMT surface chart to find the 1000-mb geopotential, and simple addition gave the SIRS 50-mb geopotentials. These were then compared with the geopotentials indicated by the analysed 'sonde' charts.

For the 49 occasions when comparisons were made in the 12 months ending May 1975, the average number of SIRS minus 'sonde' differences each day was about 45, with a minimum of 8 and a maximum of 85. For the period 3–10 March 1975 comparisons were made daily.

This method of comparison differs from that used by May (1975) who used SIRS soundings within 175 km of a radiosonde station and within two hours of 00 and 12 GMT.

Results

The variation of the mean SIRS minus 'sonde' geopotential difference during the 12-month period is shown in Figure 1. Of interest are the minimum in early December 1974 and the generally high values from January to March 1975. This could not be explained by any meteorological factor, but when the variability is examined in conjunction with the VTPR instrument in use at the time (shown at the bottom of the figure) a close correlation can be seen between changes of instrument and gross change in the difference. This is most marked in mid December 1974, when Instrument No. 1 on NOAA 3 was replaced by Instrument No. 2. The change is about 25 geopotential decametres, which corresponds to a 3-deg temperature difference in the 1000–50-mb layer. Furthermore, in addition to these gross changes, a slow continuous change of lesser magnitude is apparent in the readings from Instrument No. 1 on NOAA 2.

May (1975) had found a strong latitudinal variation in his SIRS minus 'sonde' differences, so the present data were checked and a similar variation was found. A check was made to see if there was any difference in the latitude variation between comparisons made in the Atlantic area and in the Pacific area. No statistically significant difference was found, so the comparisons from both areas were combined. The mean differences of geopotential for 10° latitude bands from 20° to 70°N are shown in Table I (together with the numbers of observations and the standard errors of the means) and they are also plotted in Figure 2. The annual mean difference is about 10 geopotential decametres, becomes zero at about 60°N, and has a slope of about $-0{\cdot}3$ dam deg^{-1}. This latitudinal variation could lead to erroneous conclusions regarding day-to-day changes in the geopotential difference, if the mean latitude of the day's comparisons changed from one day to the next. In Figure 1 the mean

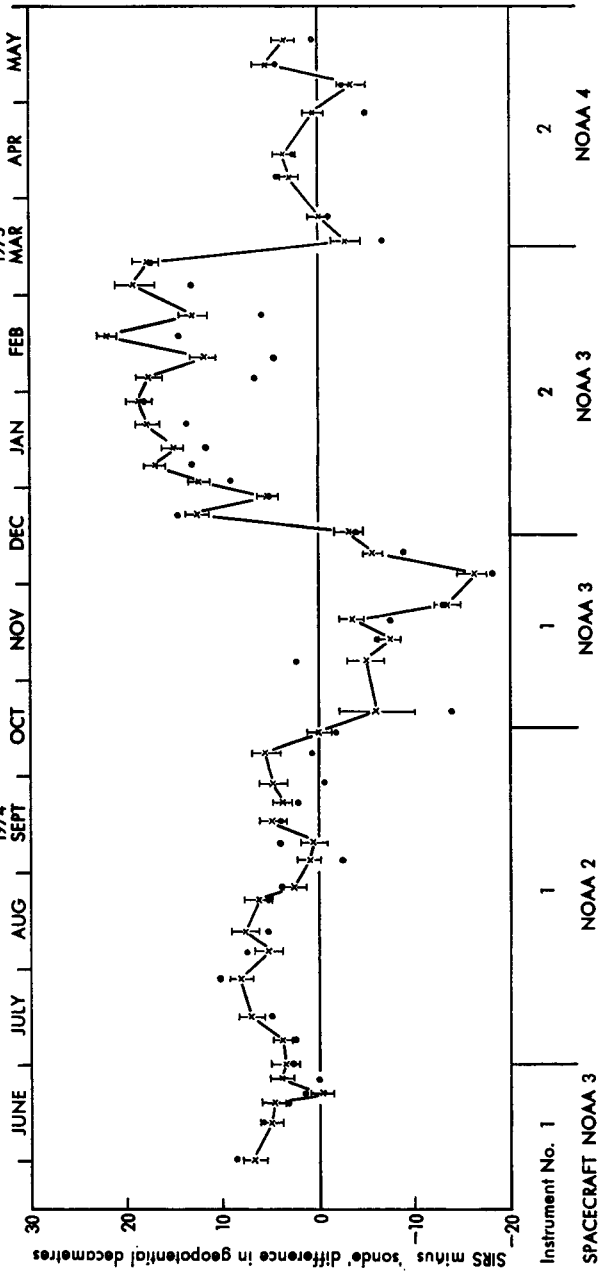

FIGURE 1—VARIATION OF 50-MILLIBAR 'SIRS' MINUS 'SONDE' GEOPOTENTIAL DIFFERENCES FROM JUNE 1974 TO MAY 1975

x differences over all latitudes. Vertical lines indicate standard errors of means.

. differences for 40°–50°N latitude band.

TABLE I—'SIRS' MINUS 'SONDE' GEOPOTENTIAL DIFFERENCES

Latitude (°N)	Annual mean	Standard error	Number of comparisons
	geopotential decametres		
60–70	−1·79	0·98	166
50–60	2·27	0·49	515
40–50	3·36	0·45	590
30–40	8·05	0·45	632
20–30	10·83	0·63	446

geopotential differences for the 40°–50°N latitude band only are also plotted, and, like the mean differences, they vary from one VTPR instrument to another, so confirming the reality of changes with instrument.

The latitudinal variation for the year is a mean over all the instruments used. For the eight-day period from 3 to 10 March 1975, when Instrument No. 2 on NOAA 3 was operational, daily comparisons were carried out, and a latitudinal variation of about −0·45 dam deg^{-1} was found, with a difference increased to 23 geopotential decametres between 20° and 30°N (see Figure 2).

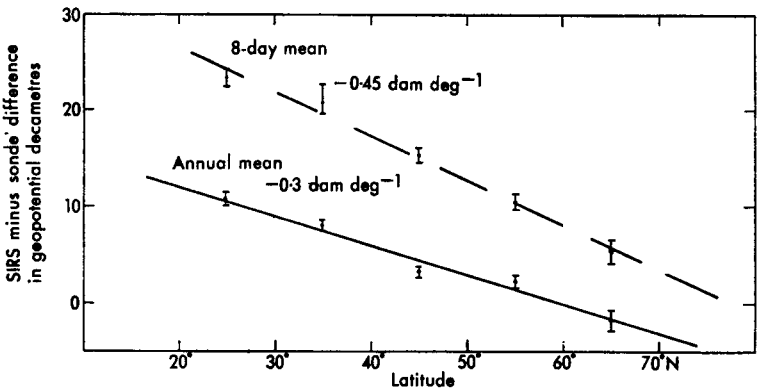

FIGURE 2—VARIATION OF 'SIRS' MINUS 'SONDE' GEOPOTENTIAL DIFFERENCES WITH LATITUDE
Vertical lines indicate standard errors of means.

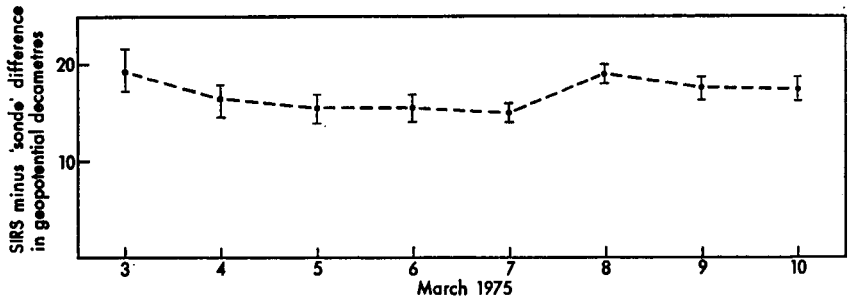

FIGURE 3—EIGHT-DAY VARIATION OF 'SIRS' MINUS 'SONDE' GEOPOTENTIAL DIFFERENCES
Vertical lines indicate standard errors of means.

The daily mean differences during the eight days are shown in Figure 3, together with the standard errors of the means. The daily average during this limited period was 1·5 geopotential decametres, with a maximum change of 4 geopotential decametres.

Conclusions

The results presented show that each VTPR instrument used during the year had a different systematic error, and that for Instrument No. 1 on NOAA 2 there was a gradual change in the error with time. Furthermore, each instrument overestimated tropical stratospheric heights. With no other observations available, the wind field derived from VTPR data would have a westerly component about 15 knots too high in mid latitudes. This would suppress the light easterly wind found in the summer at 50 mb. From a recent publication (Werbowetzki *et alii*, 1975) it appears that the technique of temperature retrieval (and hence also that of geopotential-thickness retrieval) was changed during March 1975. The reduction in SIRS minus 'sonde' difference at that time may have been caused by this change rather than by the introduction of the new instrument. Up to that time, atmospheric temperatures were calculated directly from a knowledge of the 'weighting function' for each channel in the instrument. The weighting function determines the proportion of radiation that reaches the spacecraft from a given level, and it is calculated from the spectral characteristics of CO_2 augmented by laboratory experiments. The systematic differences noted in Figure 1 indicate that there were errors in these weighting functions and perhaps also in the radiometry of each instrument.

Since mid March 1975, however, SIRS thicknesses have been found by using regression equations involving the radiances received in each channel of the instrument. The coefficients used in the equations were calculated from coincident ($\pm$80 km, $\pm$6 hour) radiosonde and VTPR data. These coefficients were progressively updated during 1975 as more coincident data were accumulated.

The new SIRS technique should produce zero geopotential difference between SIRS and sondes, and should minimize the latitudinal effect. The present study is being continued to check whether these improvements actually occur.

References

McMillin, L. *et alii*	1973	*NOAA Tech Rep* NESS 65, US Dept of Commerce, Washington, DC.
May, B. R.	1975	Results from a comparison of collocated SIRS soundings and radiosonde ascents for the period 2–16 October 1973. (Unpublished, copy available in Meteorological Office Library, Bracknell, Berks.)
Werbowetzki, A.	1975	Indirect soundings of the atmosphere from NOAA spacecraft: regression after categorization; method and results. Boston, Mass., American Meteorological Society. Proceedings of Fourth Conference on Probability and Statistics in Atmospheric Science.

551.543.5:551.466.6

A PRESSURE JUMP AND AN ASSOCIATED SEICHE AT TOBRUK

By D. H. PHILIPS
(Meteorological Office, Andover)

SUMMARY

A series of pressure oscillations with one very large, almost instantaneous, jump of 4 mb was observed at Tobruk and El Adem in March 1966 as a cold front approached and passed over these stations. A seiche of amplitude 1·6 m was apparently triggered off in Tobruk Harbour by the disturbances.

INTRODUCTION

Pressure jumps (Grimmer, 1963; Kirk, 1961, 1963a, 1963b, 1963c; Lamb, 1954; Tepper, 1950) particularly those in the Mediterranean area, have been well recorded and described. This article concerns a vigorous pressure jump of 4 mb at El Adem and Tobruk, and an apparently associated seiche in Tobruk Harbour on 25 March 1966.

THE PRESSURE JUMP

The pressure jump was first noticed at El Adem, which is situated about 22 km south of Tobruk in Libya. The duty observer at the Meteorological Office, Royal Air Force El Adem noticed at about 0200 GMT (0400 local time) that the pressure trace on the barograph had jumped upwards by about 4 mb and had immediately returned to its previous level (see Figure 1). He reported the event to Air Traffic Control, and a note was also made in the daily register of meteorological observations.

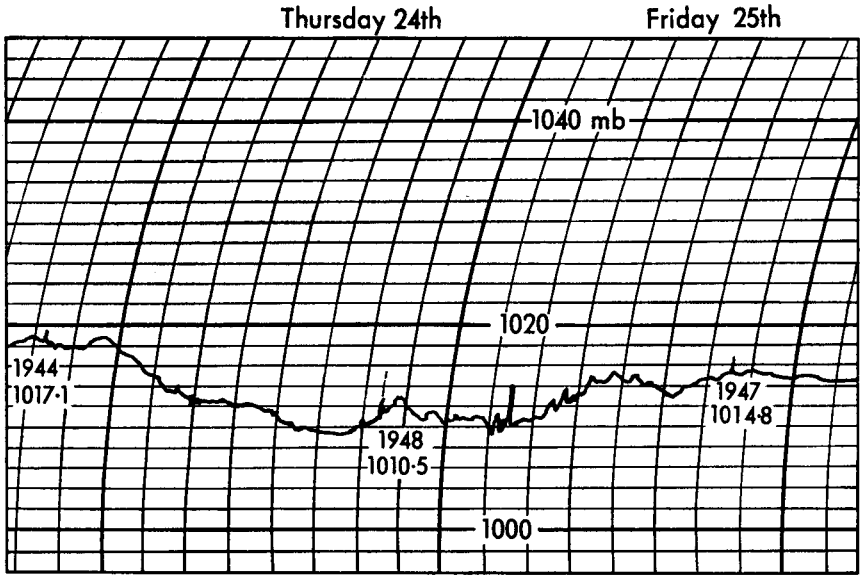

FIGURE 1—DIAGRAMMATIC REPRESENTATION OF BAROGRAPH TRACE AT EL ADEM, 23–25 MARCH 1966

Times are in local time (GMT + 2 hours).

A subsequent examination of the barogram showed that the pressure had been oscillating from about 1600 GMT on the 24th until 1100 GMT on the 25th, and indeed some of these oscillations could be treated as pressure jumps in their own right. The timing of the 4-mb jump seemed to be at about 0220 GMT.

At 0257 GMT a wind shift from 310°/12 kn to 260°/18 kn was recorded in the register. Unfortunately the anemograph was unserviceable and so no detailed wind trace could be analysed. The thermograph trace showed a sharp drop in temperature at about 1630 GMT which was in part caused by the diurnal variation but was also presumably associated with the onset of the pressure oscillations. Two further minor falls in temperature occurred at 2240 GMT and 0310 GMT (see Figure 2).

No thermogram was available from the Tobruk radiosonde station, but the barogram showed a similar pressure jump of about 4 mb at 0200 GMT and an erratic trace from 1500 GMT on the 24th until 1000 GMT on the 25th. Again, some of the oscillations could be treated as pressure jumps (see Figure 3).

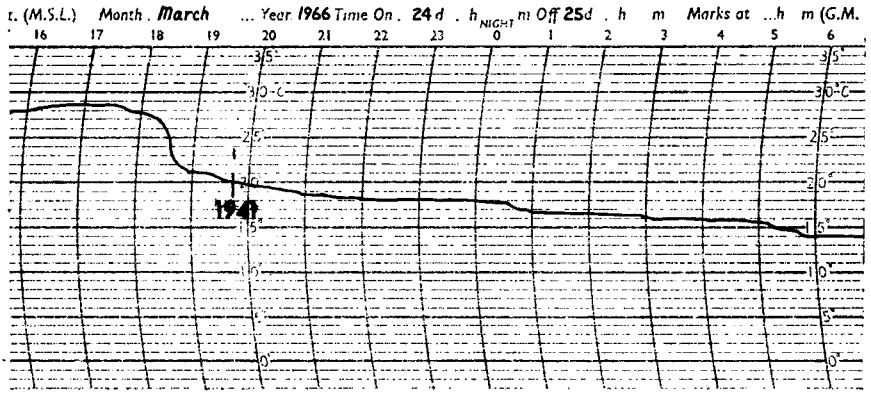

FIGURE 2—DIAGRAMMATIC REPRESENTATION OF THERMOGRAPH TRACE AT EL ADEM, 24–25 MARCH 1966

Times are in local time (GMT + 2 hours).

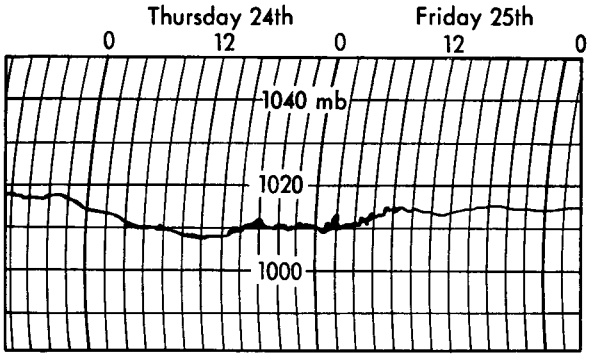

FIGURE 3—DIAGRAMMATIC REPRESENTATION OF BAROGRAPH TRACE AT TOBRUK, 24–25 MARCH 1966

Times are in GMT.

The synoptic situation

The synoptic surface charts (Servizio Meteorologico Italiano, 1966) (Figures 4–6) show that a cold front approached El Adem and Tobruk from the west-north-west, passing over Tobruk at about 0200 GMT, and over El Adem about 20 minutes later. A small low was identified to the south-west of El Adem at 0600 GMT on the 25th.

El Adem's observations, from 0058 to 0431 GMT, were as follows:

Time (GMT)	0058	0159	0245	0354	0431
Total cloud amount	8/8	8/8	8/8	8/8	8/8
Wind direction	340°	330°	310°	020°	350°
Wind speed (kn)	20	12	12	08	10
Visibility (km)	3·2	3·2	3·7	3·7	5·6
Present weather	Sand raised by wind	Slight rain	Rain in past hour	Rain in past hour	Slight rain
Past weather	Cloudy	Cloudy	Rain	Cloudy	Cloudy
Cloud	8/8 As at 12 000 ft	4/8 Ac at 8000 ft 8/8 As at 12 000 ft	3/8 Ac at 9000 ft 8/8 As at 12 000 ft	6/8 As at 10 000 ft 8/8 Cs at 20 000 ft	6/8 As at 10 000 ft 8/8 Cs at 20 000 ft
Dry bulb (°C)	17	17	16	15	—
Dew-point (°C)	13	13	14	14	—
QNH (mb)	1010·4	1011·4	1011·8	1010·4	—

QNH approximates to mean-sea-level pressure.

The observations show that there was not much 'weather' on the front—at least over El Adem. However, the Tobruk radiosonde ascent at 0000 GMT on the 25th shows a very warm, conditionally unstable layer from about 900 mb up to 600 mb. By 1200 GMT the air had been replaced by cooler, more stable air (see Figure 7). At 0000 GMT there were two tropopauses, one at 173 mb and the other at 86 mb, whereas at 1200 GMT there was only one tropopause—at 88 mb; the point at 260 mb could, however, be regarded as a tropopause. There was a strong west-south-westerly jet stream with maximum winds of 230°/151 kn at 12 400 gpm and 250°/162 kn at 11 280 gpm at 0000 and 1200 GMT respectively. The 850-mb contour lines and isotherms on the 0000 GMT upper-air chart are somewhat out of phase with those at 500 mb (see Figures 8 and 9). The 300-mb analysis chart for 0000 GMT on the 25th and the isallobaric chart for 1800 GMT on the 24th have been included in order to give a more complete picture of the synoptic situation (see Figures 10 and 11).

A seiche in Tobruk Harbour

At about 0915 GMT on the 25th, the sergeant on duty at the RAF Marine Section in Tobruk Harbour rang to say that the water level there was fluctuating by 1·6 metres or more in 15 to 20 minutes and that the water was flowing at speeds of up to 10 kn past his boats, but that there were no waves. This, he said, had been going on since 0600 GMT. It is not clear whether the oscillations started at 0600, or whether that is when they were first noticed. A check made later on in the morning gave the amplitude as 1·6 m, and the period, between high waters, as 24 minutes. The rise and fall was still detectable two days later.

Discussion

Kirk (1963b) suggests that an explanation of a pressure jump could be:

(a) a sharp drop in tropopause height, and

(b) the occurrence of out-of-phase relationships at different levels.

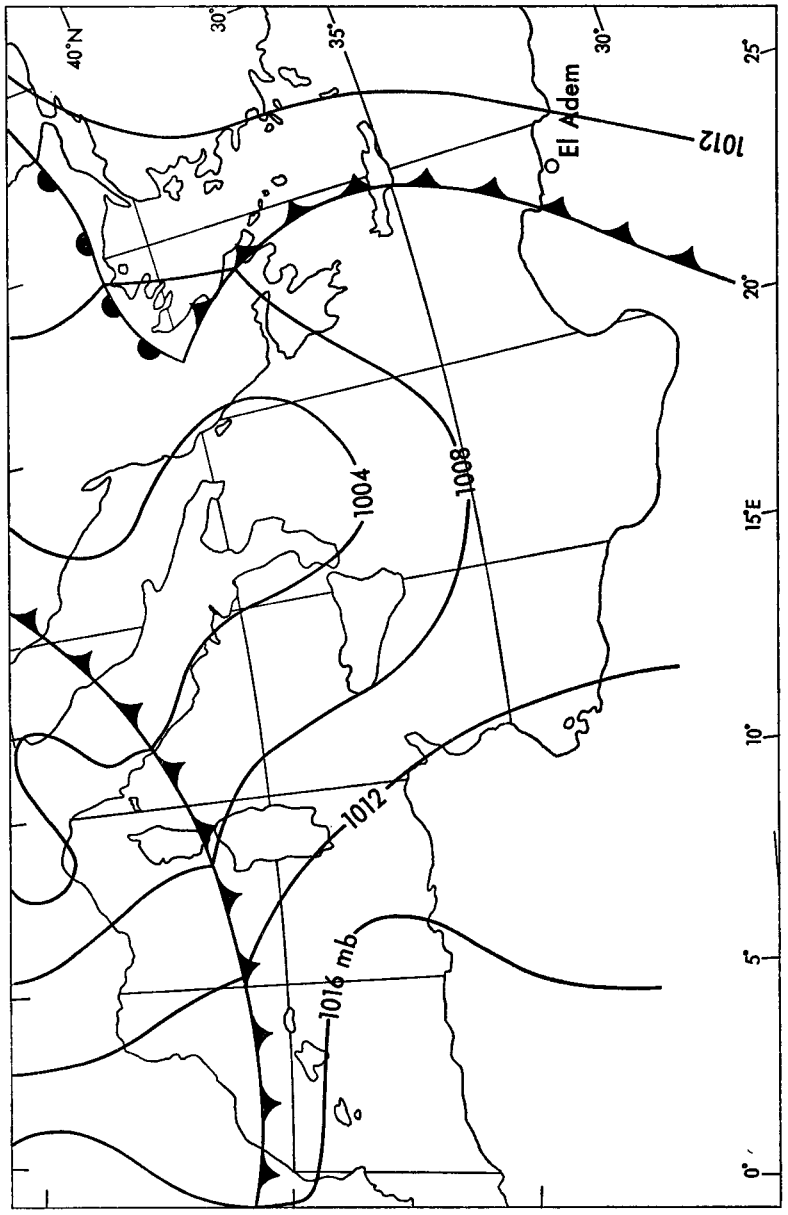

FIGURE 4—SURFACE ANALYSIS FOR 18 GMT, 24 MARCH 1966

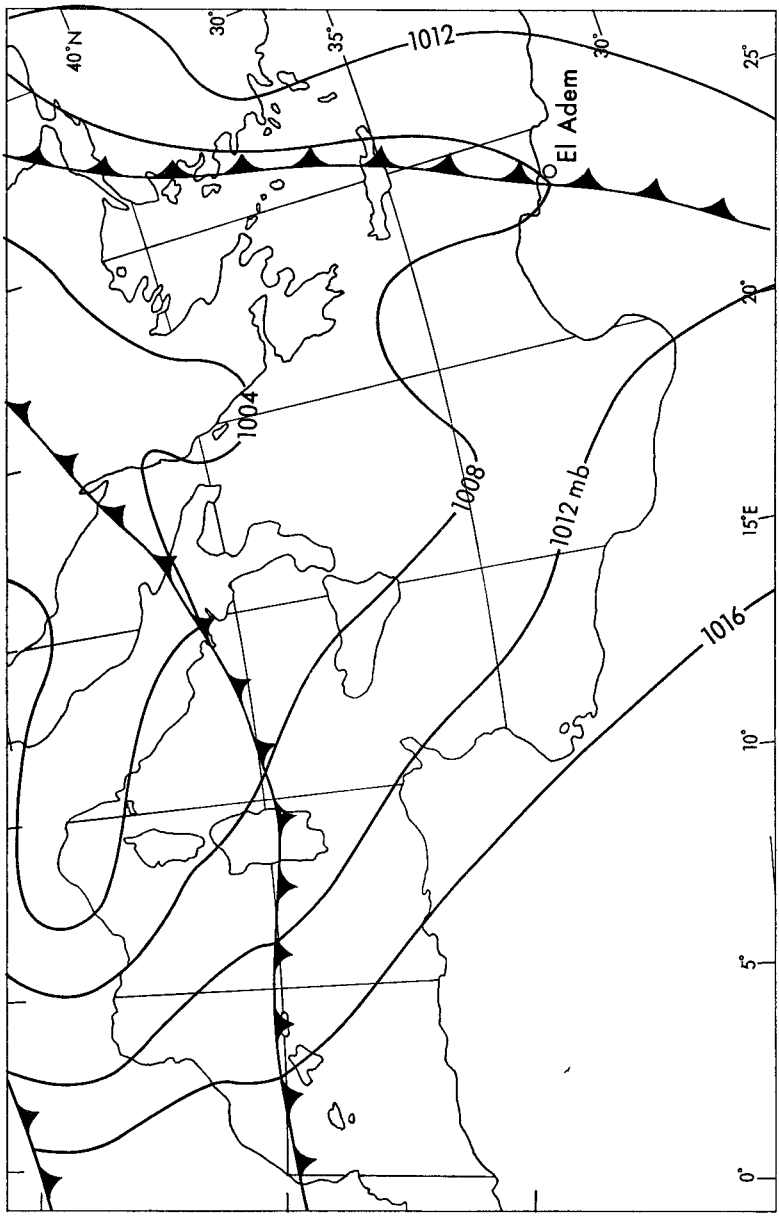

FIGURE 5—SURFACE ANALYSIS FOR 00 GMT, 25 MARCH 1966

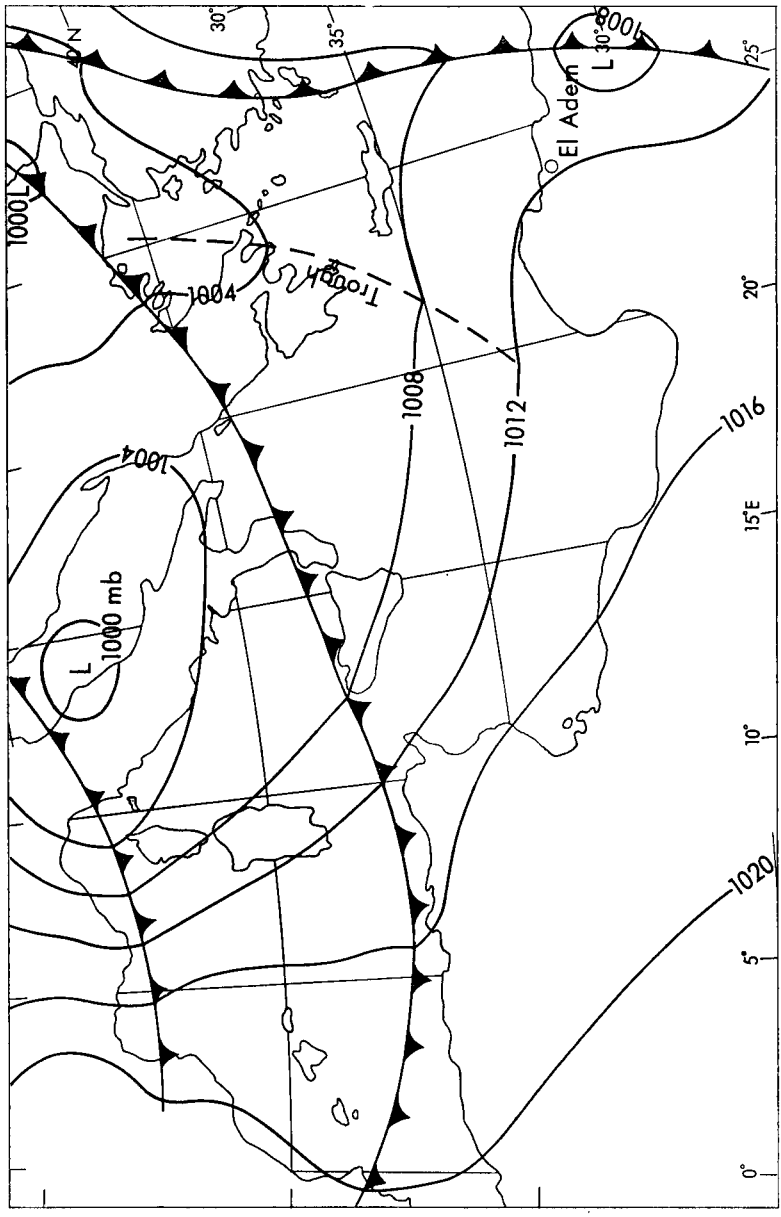

FIGURE 6—SURFACE ANALYSIS FOR 06 GMT, 25 MARCH 1966

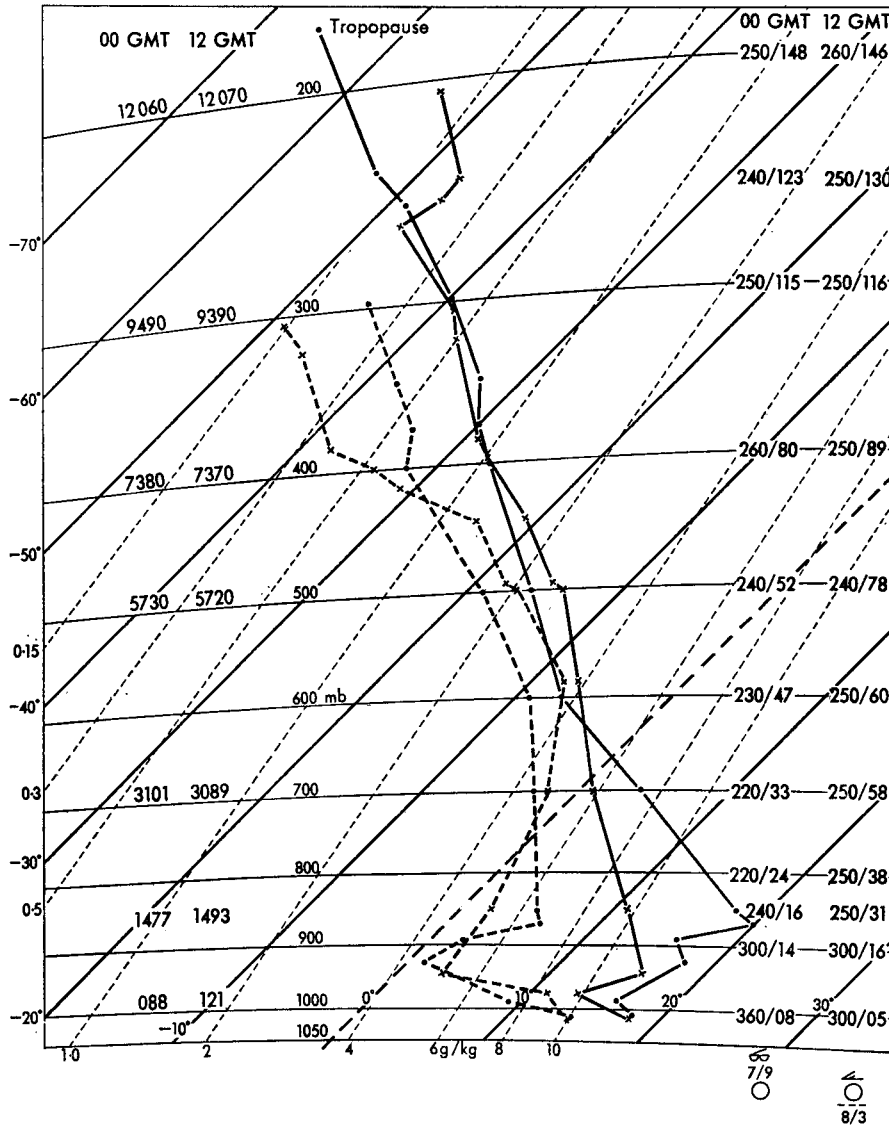

FIGURE 7—RADIOSONDE ASCENTS AT TOBRUK, 25 MARCH 1966

· ——— · 00 GMT dry-bulb temperature.
· - - - · 00 GMT dew-point temperature.
x —— x 12 GMT dry-bulb temperature.
x - - - x 12 GMT dew-point temperature.

Geopotentials in geopotential metres are shown at the left-hand side and winds in degrees true and knots at the right-hand side.

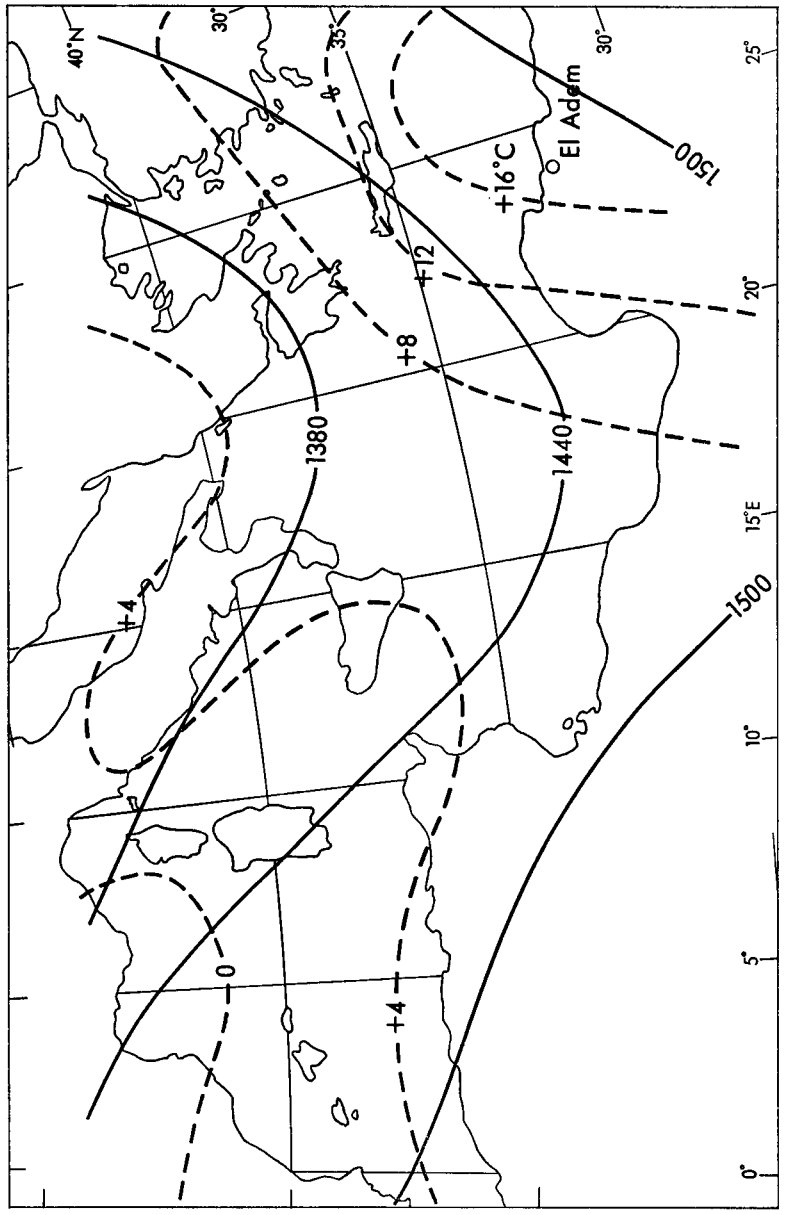

FIGURE 8—850-mb ANALYSIS FOR 00 GMT, 25 MARCH 1966

——— heights in geopotential metres.
– – – – temperatures in degrees Celsius.

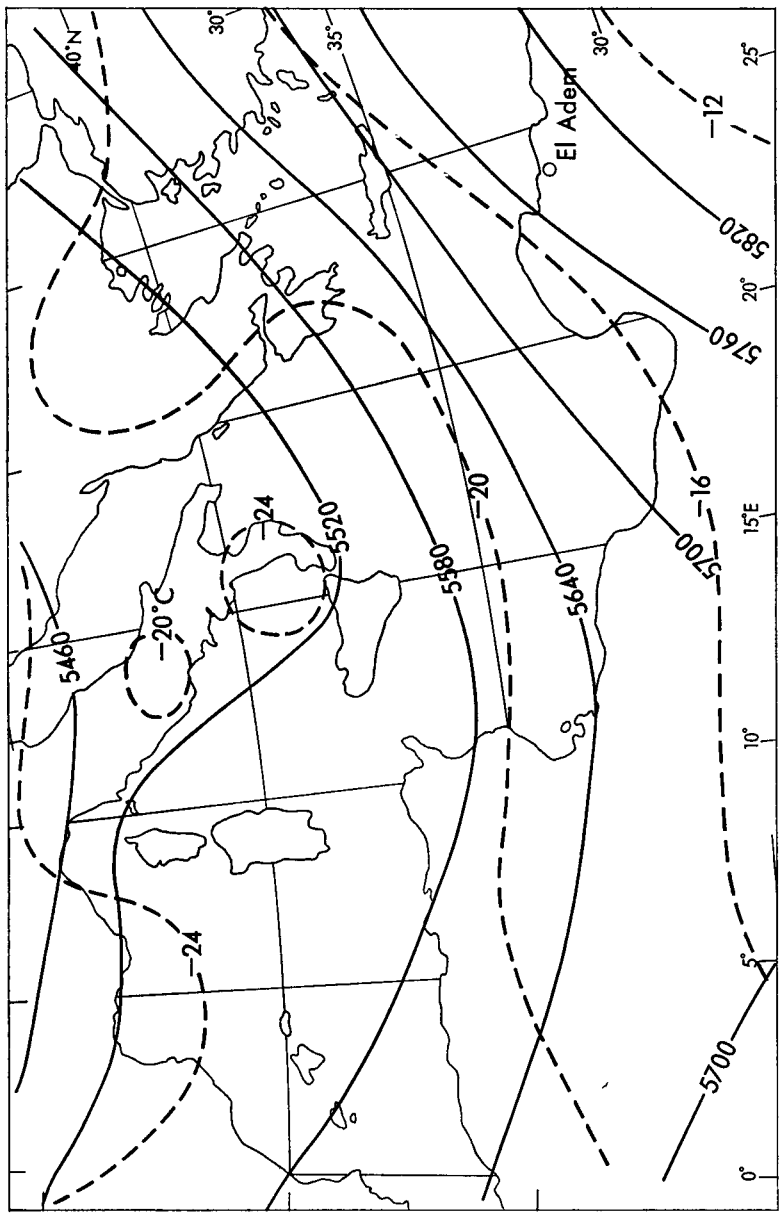

FIGURE 9—500-mb ANALYSIS FOR 00 GMT, 25 MARCH 1966

——— heights in geopotential metres.
– – – – temperatures in degrees Celsius.

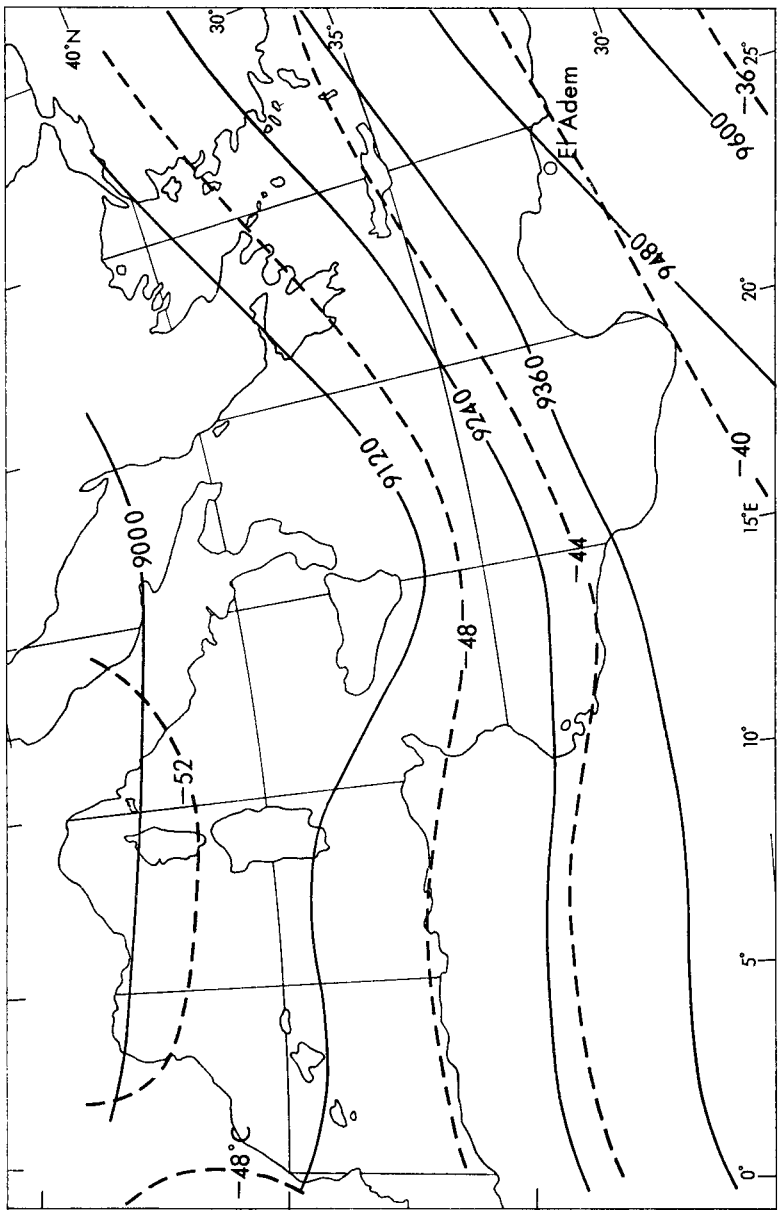

FIGURE 10—300-mb ANALYSIS FOR 00 GMT, 25 MARCH 1966

——— heights in geopotential metres.
- - - - temperatures in degrees Celsius.

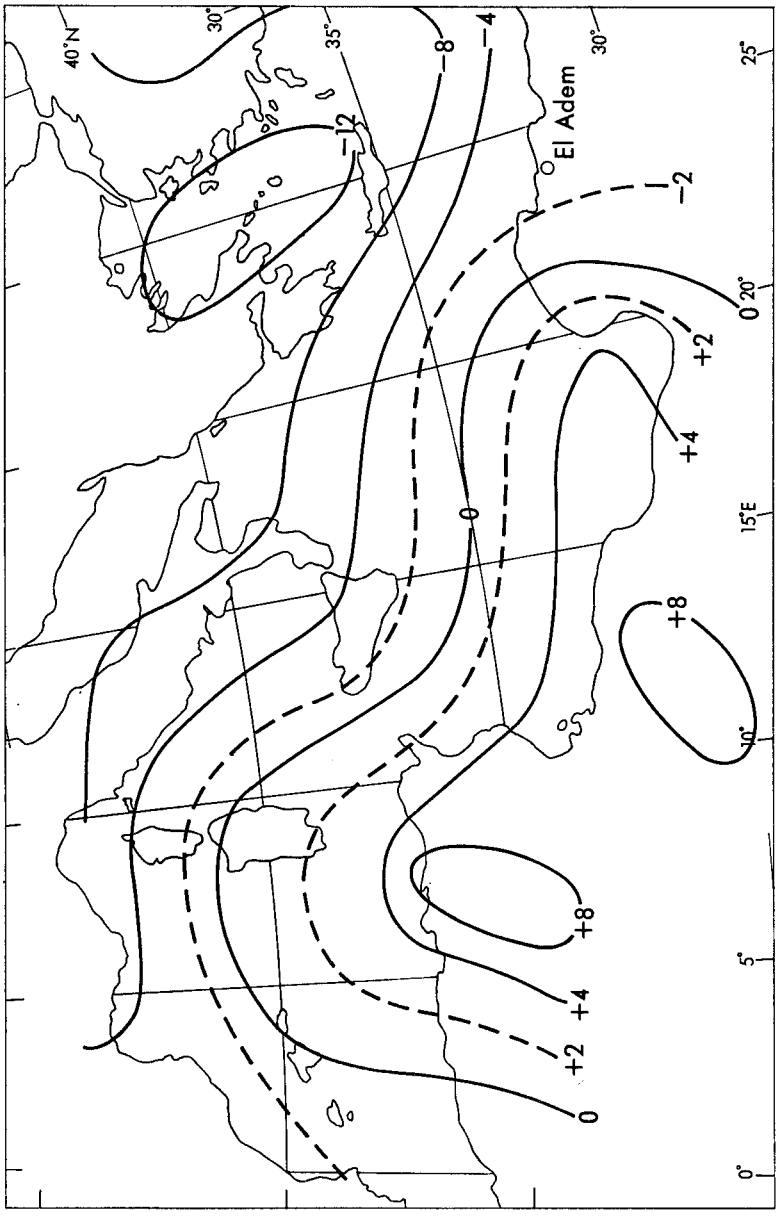

FIGURE 11—ISALLOBARIC CHART FOR 18 GMT, 24 MARCH 1966

Isopleths indicate pressure changes in millibars during the preceding three hours.

Lamb (1954) offered the explanation that possibly a ripple on an old degenerate front could cause a pressure jump, while Tepper (1950) considered that the action of an accelerating cold front, causing a gravity wave to travel ahead of itself at a speed greater than the frontal speed, was analogous to the action of a piston (Freeman, 1948) where the leading edge of the wave becomes almost vertical, thus creating a 'jump'.

In the instance under discussion it seems that there was a series of waves propagated ahead of the cold front. There was also a lowering of the tropopause, and the 850- and 500-mb levels were out of phase. However, pressure jumps can occur in thundery weather and so, because of the scarcity of observations over Libya, it is felt that no firm conclusions can be drawn about the cause of the pressure jumps.

Theoretical values for the period of oscillation for lakes of various shapes, sizes and depths have been derived by several workers, (e.g. Chrystal, 1905), but lack of precise knowledge of all the necessary parameters in practical cases combined with inevitable departures from the simplicity of the theoretical models makes comparisons with observed values generally unrewarding. Oscillations have happened before in Tobruk Harbour, according to the Harbour Master at that time. He said that they happened every year or two but that he had no record of dates of occurrence.

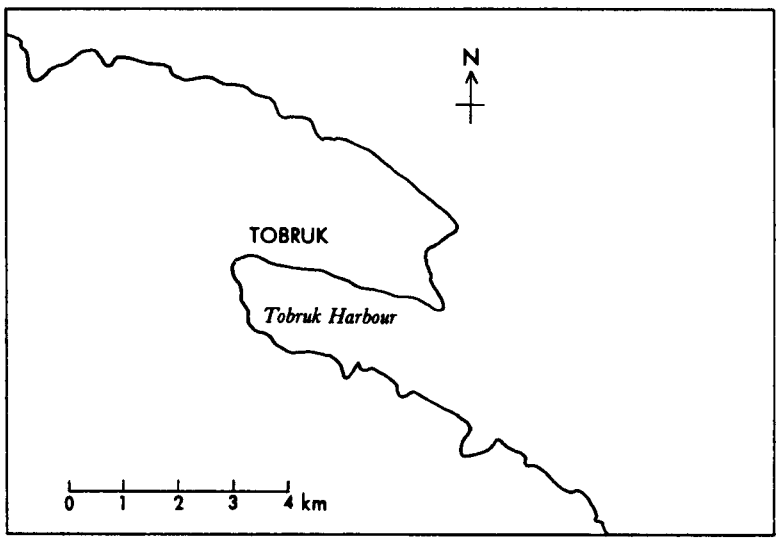

FIGURE 12—MAP SHOWING THE SHAPE OF TOBRUK HARBOUR

Chrystal and others have suggested that seiches can be triggered off by atmospheric disturbances. Seiches occur in lakes, harbours, estuaries, and even over shelving beaches; therefore if it can be accepted that pressure jumps can trigger off seiches, then it becomes important to find a way of forecasting them, particularly in these days of supertankers which often have only one or two metres clearance from the sea bed; seiches superimposed on storm surges may also aggravate flooding.

ACKNOWLEDGEMENT

The author wishes to thank Mr T. H. Kirk, who read a first draft of this article and suggested improvements.

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551.509.323:551.525

A STATISTICAL METHOD OF FORECASTING GRASS-MINIMUM TEMPERATURES AT WEST RAYNHAM

By M. N. PICKUP

(Meteorological Office, West Raynham*)

SUMMARY

The variation with wind speed and cloudiness of the difference between screen-minimum and grass-minimum temperatures at West Raynham, Norfolk, was investigated by use of hourly synoptic data from a 10-year period. Mean values of this difference decreased rapidly with increasing wind speed on clear nights, but little variation was found on cloudy nights. There was no significant variation with screen-minimum temperature.

INTRODUCTION

Forecasts of grass-minimum temperatures are required by farmers and horticulturists, expecially in spring and summer when damage to young plants can be avoided provided that sufficient warning can be given.

It is common practice to forecast the minimum screen temperature expected overnight (2100 to 0900 GMT) and then to adjust this figure in the light of the forecast cloud cover and wind strength to give the forecast grass-minimum temperature.

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Craddock and Pritchard (1951) in an investigation based on 16 stations in England found that with light winds the difference (Δ) between the screen-minimum and grass-minimum temperatures averaged 4 deg both for mainly clear and for mainly cloudy nights. For nights with clear skies at Northolt, Saunders (1952) obtained an average value of about 6 deg for Δ for geostrophic wind speeds of 17–24 kn and for wind speeds both below and above this range an average value of about 4–4½ deg. Experience at West Raynham suggests a greater range of Δ and the purpose of this investigation is to obtain values of Δ appropriate to West Raynham.

Data

The data used were the hourly full synoptic observations for West Raynham over the period 1 January 1961–19 March 1970. These were continuous with the exception of the period August 1969 to March 1970 when observations were not made at weekends.

West Raynham lies about 80 m above sea level, some 20 km inland from the northern coast of Norfolk. The airfield is sited on a small plateau and the soil is officially described as 'rather stony loam' which affords good drainage.

The anemometer tower is situated on the roof of the Air Traffic Control building approximately 30 m north of the instrument enclosure. A correction of −10 per cent is made to the recorded wind strength in view of the fact that the height of the cups is 16 m above ground level.

The instrument enclosure is sheltered from the north-west by blast ramps, hangars and other buildings, but freely exposed in other directions.

Method of analysis and results

A total of 3240 nights were examined and of these 639 (19·7 per cent) were classified as 'clear'. A 'clear' night was defined as one with less than 2/8 low and/or medium cloud at each hourly observation between 2100 and 0900 GMT. Nights with cirriform cloud were included but nights with fog were excluded. A further 399 nights (12·3 per cent) were classified as 'cloudy'. A 'cloudy' night was defined as one with 8/8 low and/or medium cloud at each hourly observation between 2100 and 0900 GMT. On 239 of these nights the cloud base was below 2000 ft (approximately 600 m) and on 160 nights the base was above 2000 ft.

For each 'clear' and 'cloudy' night the average surface wind speed and predominant surface wind direction over the period from 2100 to 0900 GMT were obtained. A few nights which showed large variations in wind speed were excluded and also some nights with variable wind directions, but generally the wind direction which predominated was easily selected.

The difference (Δ) between the screen-minimum and grass-minimum temperatures was calculated for each of the 'clear' and 'cloudy' nights. These values of Δ for 'clear' and 'cloudy' nights were studied separately. They were also grouped according to (a) surface wind speeds of 1–5, 6–10, 11–15 and above 15 kn, and (b) surface wind directions in the NE, SE, SW and NW quadrants. For 'cloudy' nights the values of Δ were initially analysed separately for those nights with cloud base above and below 2000 ft, but the values of Δ were found to be similar, and in the final analysis the distinction was not retained. For each combination of wind speed and direction the mean value

of Δ was obtained together with the maximum value, and (for the 'clear' nights only) the standard deviation. Results are shown in Tables I and II for 'clear' and 'cloudy' nights respectively.

A separate analysis was made of Δ on occasions when the screen minimum was near or below 0°C for nights with 'clear' skies and winds less than 10 kn. This sample produced 177 (5 per cent) occasions when the screen minimum was between +1·9°C and −10·0°C. These values were split into four 3-deg intervals, and the mean and standard deviation for Δ in each range are shown in Table III. In addition, the values of Δ with screen minimum between +1·9°C and −6·0°C, 170 occasions, were split into eight 1-deg intervals, and the mean and standard deviation in each range are shown in Table IV.

During this work some notice was taken of other meteorological variables such as humidity, dew and frost. These were not analysed numerically, but they give rise to some of the comments made in the discussion below.

Discussion

Table I ('clear' nights) shows that for all wind directions there is a decrease of the mean value of Δ with increasing wind speed. The same may almost be written of the variability of Δ, but there are exceptions in that as the winds increase from 1–5 to 6–10 kn, the standard deviations increase slightly in the NE and SE sectors, and change very little in the other two sectors. For similar

TABLE I—DEPRESSION (Δ) OF GRASS-MINIMUM TEMPERATURE BELOW SCREEN-MINIMUM TEMPERATURE AT WEST RAYNHAM ON NIGHTS WITH 0–2/8 LOW AND/OR MEDIUM CLOUD

Total number of 'clear' nights 639

	Number of 'clear' nights	Mean difference (Δ)	Standard deviation	Highest Δ
Average wind speed 1–5 knots			*degrees Celsius*	
NE'ly (010–090°)	23	6·1	1·1	7·7
SE'ly (100–180°)	24	5·1	1·0	7·1
SW'ly (190–270°)	38	5·1	1·0	8·0
NW'ly (280–360°)	33	5·3	0·9	7·5
Average wind speed 6–10 knots				
NE'ly	57	3·8	1·3	6·8
SE'ly	82	4·3	1·3	8·6
SW'ly	147	3·5	1·0	6·0
NW'ly	41	3·1	0·8	4·5
Average wind speed 11–15 knots				
NE'ly	22	2·4	0·6	3·4
SE'ly	19	2·0	0·5	2·9
SW'ly	71	2·0	0·4	3·5
NW'ly	23	2·2	0·6	3·4
Average wind speed above 15 knots				
NE'ly	3	1·6	—	1·8
SE'ly	Nil			
SW'ly	50	1·7	0·4	2·8
NW'ly	6	1·7	0·4	2·3

TABLE II—DEPRESSION (Δ) OF GRASS-MINIMUM TEMPERATURE BELOW SCREEN-MINIMUM TEMPERATURE AT WEST RAYNHAM ON NIGHTS WITH 8/8 LOW AND/OR MEDIUM CLOUD

Total number of 'cloudy' nights 399

	Number of 'cloudy' nights	Mean difference (Δ)	Highest Δ
Average wind speed 1–5 knots		*degrees Celsius*	
NE'ly (010–090°)	17	0·7	1·6
SE'ly (100–180°)	4	0·9	1·8
SW'ly (190–270°)	9	0·8	1·6
NW'ly (280–360°)	16	1·1	2·0
Average wind speed 6–10 knots			
NE'ly	43	0·8	2·3
SE'ly	20	0·9	2·6
SW'ly	36	0·9	2·5
NW'ly	18	0·9	1·9
Average wind speed 11–15 knots			
NE'ly	81	0·6	2·2
SE'ly	22	0·9	2·0
SW'ly	33	0·9	1·6
NW'ly	20	0·9	2·0
Average wind speed above 15 knots			
NE'ly	31	0·5	2·0
SE'ly	14	0·7	1·3
SW'ly	29	0·9	2·0
NW'ly	6	0·6	1·0

conditions at Northolt Saunders (1952) obtained mean values of Δ of about 4½ deg, 6 deg, and 4 deg for geostrophic wind speeds of 0–16, 17–24 and over 24 kn respectively, and suggested an explanation of these variations in terms of turbulent mixing. Allowing for the likely difference between surface and geostrophic wind speeds, there is reasonable agreement between the mean value found by Saunders for Δ in his 0–16-kn range, and those found in this investigation, but there is no evidence in the West Raynham results of his temporary increase of mean Δ with increasing wind speed.

The mean and standard deviation of Δ show relatively little change with wind direction. The highest mean value of 6·1 deg is associated with the NE quadrant and the overall maximum of 8·6 deg with the SE quadrant. Light easterly winds which give clear skies over Norfolk are often associated with very dry continental air which may account for the extreme values occurring in these sectors. It was noticed during the investigation that there was a greater fall of ground temperature when the air was dry initially and when subsequently no dew or frost formed. All the highest values of Δ occurred in 'dry' air. The overall maximum of 8·6 deg with a south-easterly wind of 6–10 kn was in fact a borderline case, as the wind overnight averaged 6 kn.

During the analysis it was found that values of Δ between 6·2 deg and 8·6 deg occur each month, with little obvious variation between summer and winter.

It was also noticed that although grass-minimum temperatures officially refer to the period from 2100 to 0900 GMT, large differences between screen and grass temperature often occur before 2100 GMT on occasions of light winds with clear skies. For example on 26 March 1973 (sunset 1824 GMT) the screen temperature at 1900 was 7·4°C and the grass temperature −3·0°C, a difference of 10·4 deg. It is important to remember that such large differences can occur shortly after sunset.

Table II ('cloudy' nights) shows that mean values of Δ are similar for all wind directions and speeds, being generally a little below 1 deg. The maximum values are also rather similar and mostly about 2 deg. In view of the relatively small differences between mean and maximum values, standard deviations were not calculated for this sample. The overall maximum value of 2·6 deg must be slightly suspect, as there can be no guarantee that the cloud did not break during nights when all the hourly observations were of 8/8 cloud.

Tables III and IV were produced to determine whether changes of Δ occur at West Raynham which are similar to those found by Saunders for Northolt on clear winter nights with light winds or calms, Table III having ranges of screen-minimum temperature corresponding to the °F ranges used in Saunders's own Table III, and Table IV having finer subdivisions. Saunders found in such conditions that as the screen-minimum temperature decreases from about +1°C to −8°C, mean values of Δ increased from about 2 deg to 6 deg, and suggested an explanation in terms of latent-heat effects. Both tables indicate that the variation in Δ found at Northolt does not occur at West Raynham, and there is no significant change in either the mean or the standard deviations of Δ around 0°C. Individual values of Δ between 6·3 deg and 8·6 deg were found in all the class intervals of Table IV.

TABLE III—DEPRESSION (Δ) OF GRASS-MINIMUM TEMPERATURE BELOW SCREEN-MINIMUM TEMPERATURE ON 'CLEAR' NIGHTS WITH LIGHT WINDS AT WEST RAYNHAM FOR VARIOUS RANGES OF SCREEN-MINIMUM TEMPERATURES (T_{min})

T_{min} (°C)	+1·9 to −1·0	−1·1 to −4·0	−4·1 to −7·0	−7·1 to −10·0
Number of occasions	73	70	29	5
Mean depression (Δ)	4·3 deg	4·5 deg	3·8 deg	4·4 deg
Standard deviation	1·3 deg	1·5 deg	1·4 deg	1·3 deg

TABLE IV—DEPRESSION (Δ) OF GRASS-MINIMUM TEMPERATURE BELOW SCREEN-MINIMUM TEMPERATURE ON 'CLEAR' NIGHTS WITH LIGHT WINDS AT WEST RAYNHAM FOR A GREATER NUMBER OF NARROWER RANGES OF SCREEN-MINIMUM TEMPERATURE (T_{min})

T_{min} (°C)	+1·9 to +1·0	0·9 to 0·0	−0·1 to −1·0	−1·1 to −2·0
Number of occasions	25	22	26	30
Mean depression (Δ)	4·6 deg	3·9 deg	4·3 deg	4·7 deg
Standard deviation	1·1 deg	1·4 deg	1·3 deg	1·5 deg

T_{min} (°C)	−2·1 to −3·0	−3·1 to −4·0	−4·1 to −5·0	−5·1 to −6·0
Number of occasions	23	17	15	12
Mean depression (Δ)	4·5 deg	4·1 deg	4·2 deg	3·5 deg
Standard deviation	1·3 deg	1·8 deg	1·3 deg	1·4 deg

'Student's'-*t* tests were made on the apparent differences between the mean Δ for West Raynham in Table III, and Saunders's values for corresponding temperature ranges, on the assumptions (i) that Saunders's standard deviations were the same as those in Table III, and (ii) that the ratio of the number of events in each class, used by Saunders and in the present investigation, is a constant—equal to the ratio of the lengths of the two periods considered, i.e. two winters by Saunders to 10 winters here. Results of these *t*-tests indicate (i) that for the first temperature range there is less than 1 chance in 100 of such a large mean difference arising by accident of the samples if there is really no difference in behaviour at the two sites; (ii) that for the third temperature range there is about a 6 per cent chance of finding such a large mean difference by accident of the samples; and (iii) that for the other temperature ranges the apparent differences could easily arise by chance.

It was noted during nights when there were breaks in the cloud for periods of even one or two hours that rapid falls of ground temperature could occur. Nights with variable cloud were not analysed objectively, but for such nights with moderate wind Δ is about 2 deg.

Conclusions

For 'clear' nights the mean value of Δ for West Raynham decreases rapidly with increasing surface wind speed from 5 to 6 deg for light winds to about 1½ deg for winds above 15 kn. It shows little variation with wind direction. The standard deviation of Δ decreases from about 1 deg for surface winds up to 10 kn to about 0·5 deg for stronger winds. Maximum values of Δ within the range 6·2 to 8·6 deg occur each month (with winds less than 10 kn) with little variation between summer and winter.

For cloudy nights the mean value of Δ is similar for all wind speeds and directions, being in general a little below 1 deg. Maximum values of Δ for such nights are mainly within the range 1·5 to 2·5 deg.

For 'clear' nights with light winds the variation in Δ with screen-minimum temperatures near or below 0°C which Saunders detected in the winter at Northolt is not apparent at West Raynham. For such conditions a mean value of Δ of 4·3 deg is appropriate at West Raynham.

During nights when there are breaks in the cloud for periods of even one or two hours, rapid falls of ground temperature occur, especially with light winds. On occasions of light winds with clear skies large differences between screen and grass temperatures can occur shortly after sunset, for example a difference of 10·4 deg within one hour of sunset on 26 March 1973.

Acknowledgement

The author would like to thank Mr C. L. Hawson for help in the preparation of this paper.

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551.501.816:061.3

MEETING REPORT—SEVENTH INTERNATIONAL LASER RADAR CONFERENCE, PALO ALTO, CALIFORNIA, 4–7 NOVEMBER 1975

By R. E. W. PETTIFER

The Seventh International Laser Radar Conference was a highly successful meeting for which nearly two hundred scientists from all over the western world gathered at the Stanford Research Institute in Palo Alto, California. Unfortunately the Russian and other east European contributors did not attend and their papers were read by title only: a sad omission from the program. Nevertheless, the fact that laser radar techniques are now firmly established as fruitful means of atmospheric investigations at levels up to 100 km was evidenced by the crowded and comprehensive program in which more than 70 papers were presented.

The main emphasis of the meeting was on the development of new laser techniques or the improvement or extension of existing laser methods for atmospheric studies. Professor R. M. Schotland outlined an interesting development of the Doppler laser radar concept in which the use of two nearly equal output frequencies leads to detection of a signal at their difference frequency. Since this difference frequency will be of the order of kilohertz or megahertz rather than the gigahertz of the output laser frequency, there is a consequent relaxation in the band-width and frequency-stability requirements in the detectors.

There was considerable emphasis on the detection of gaseous trace constituents in the troposphere, especially pollutants in the boundary layer, by the Differential Absorption and Scattering technique (DASE, also called DIAL or DISC) which seems to have gained favour over the less sensitive, though technically more straightforward, vibrational Raman method. The bulk of the work reported using the DASE technique had been directed to the detection of tropospheric water vapour, and although the theory and feasibility of the work was demonstrated over a wide range of wavelengths in the red and infra-red, no new atmospheric measurements were presented. The applications of the technique to the measurement of pollutants such as SO_2 and HCl in effluent from various sources and even of naturally occurring stratospheric OH were also discussed.

Two complementary papers on the signal-induced noise effects in certain photomultipliers produced some lively discussion between groups of believers and unbelievers, but there seems to be emerging a weight of evidence to support the existence of these effects in many different types of photomultiplier.

A long session of the meeting was devoted to the results of observations of stratospheric aerosols, a topic of especial relevance in 1975 following the Fuego Volcano eruption in 1974. Some interesting correlations between the characteristics of the well-marked dust layer and other stratospheric parameters were illustrated. For example, work by NASA scientists under the leadership of Dr M. P. McCormick has shown that the level of the peak in the ratio between backscatter from the dust and from the air at the same level was well correlated with the level of minimum temperature of the stratosphere, that the vertical extent of the dust layer was associated with the vertical extent of a

layer of air colder than the average stratospheric temperature, and that increases in the mass loading of the dust layer were correlated with increases in the minimum or average stratospheric temperature. Many other topics concerning stratospheric aerosol were discussed, including most likely formation mechanisms, transport processes, a marked correlation of aerosol concentration with decreases in maximum ozone amount at the ozone peak, and deductions about size distributions and refractive index. There were two presentations of novel approaches to stratospheric work. In one, Dr J. Reagan and his colleagues at the University of Arizona, Tucson described a very comprehensive experiment involving simultaneous measurements using bi-static lidar and a seven-channel tracking solar radiometer. In the other, Dr R. E. W. Pettifer of the Meteorological Office presented results of the difficult but potentially useful technique utilizing the vibrational Raman scattering from nitrogen to obtain air-density measurements that are unaffected by the presence of aerosols and from which the first stratospheric temperature profiles obtained by laser radar methods have been derived. He also presented the results of a two-wavelength Rayleigh/Mie backscattering experiment that is free from the ambiguities introduced into single-wavelength experiments by the normalization process.

A new development at the conference was the devotion of a complete session to meteorological observations by lidar. This group of papers served to illustrate that such techniques are still in their infancy. However, it included a description of a comprehensive 'present-weather' monitoring system that has been built and which, it is hoped, will yield information in real time on visibility and on precipitation type and rate. Several papers dealing with remote measurements of wind or turbulence were presented, including the preliminary results of investigations into the dynamical structure of dust devils. Horizontal and slant visual range experiments were also discussed.

The very extensive work in progress at the Stanford Research Institute and at the University of Arizona on the nature and dynamics of the tropospheric aerosols, especially in the boundary layer, was illustrated in a series of papers from these two sources. From the work at Tucson, a good fit to the laser scattering results was obtained by fitting a two-component Bode model aerosol distribution with a real refractive index of 1·4 in a particle-size range of from 0·02 μm to 5 μm. Similar boundary-layer work at NOAA was reported, in which a two-component log-normal size distribution with peaks at 10^{-1} μm and 50 μm was postulated. Additional tropospheric work reported included the study of the development of snow precipitation from a cloud consisting initially of two well-separated regions, one of liquid drops, the other of ice crystals; attempts to measure rainfall rate by a single-ended backscatter lidar, and an extensive study of the relationships between backscatter and extinction in fogs.

The conference concluded with two sessions on theoretical scattering studies involving the effects of irregularly shaped particles and spherical aerosols. It is clear from the work reported that the complications of irregularity in particle shape are as yet not being fully accounted for in most laser radar work, and the result, announced by Dr G. Grams of NCAR, that backscatter from non-spherical particles can be as much as one order of magnitude less than from equivalently sized spheres, is an indicator of the possible extent of the problem.

It is clear from the vigorous character of this valuable and interesting meeting that the use of lasers for a wide range of atmospheric sounding experiments is

now an established and expanding field from which in the next decade a great deal of data on the nature of the atmosphere, its structure, composition and small-scale dynamics may be expected.

REVIEWS

Climate in a small area, by Masatoshi M. Yoshino. 265 mm × 190 mm, pp. xvi + 549, *illus.*, International Book Distributors Ltd, 66 Wood Lane End, Hemel Hempstead, Herts. HP2 4RG, 1975. Price: £16.

The volume under review is a revised and enlarged version, written in English, of a work in Japanese which appeared in 1961. In its declared scope, layout and approach, it calls to mind Geiger's classic *Climate near the ground*, which first appeared in 1927 and is now in its fourth edition (Harvard University Press, 1965). A review may therefore profitably take the form of a comparison of the two books.

The complex interaction of local topography, ground surface conditions and prevailing weather which gives rise to the climate experienced over a particular small area probably dictates that any account of the subject shall be rather fragmented. It is always much more difficult to present a coherent unified theory than to quote specific examples (of, say, valley winds or frost-pocket temperatures). Both books suffer from this difficulty, but Yoshinò succeeds in sifting out gratuitous detail from his examples, which allows a clearer picture to emerge. Also, the chapters of the new book are subdivided much more explicitly and so, with better indexing than Geiger, it is possible to trace topics much more easily.

There is a slight difference in the space scales of the phenomena described by the two authors. Geiger's range can perhaps be considered to be 10^{-2} to 10^{4} m, whereas Yoshino's is somewhat higher (say, 10^{1} to 5×10^{4} m). Yoshino omits what might be called 'agricultural micro-climatology' (Geiger devotes a whole chapter to the air layer near plant-covered ground), but gives very extensive coverage to phenomena at the larger-scale end of the 'local climate' range. His chapter on 'Local airstreams and weather' occupies 130 pages and includes many examples of local climatic effects having space scales of tens of kilometres and their relationship with conditions on the synoptic scale. Japanese examples, naturally, provide the bulk of the material, but many European, American and Russian cases are also quoted and discussed. The section on local winds is particularly comprehensive. Yoshino also gives much wider coverage than Geiger in the field of urban climate, where there has been a considerable increase in both observational and theoretical studies over the last decade.

In the final chapter, examples are given of the importance of local climate for plant ecology (particularly the influence of wind on tree growth) and geomorphology (including erosion due to wind, rain and ice).

The book is well presented, with clear diagrams and the written style is generally good. There is the occasional quaintness of expression which inevitably arises from an author working in a second language (for example, in one diagram, four categories of frost risk are defined as '(a) frequent frost, (b) frost once or twice a year, (c) frost experienced once or twice by old men, (d) frost is rare').

The wealth of detail in Geiger's work and his constant awareness of the basic physical processes at work in local climate make it difficult to imagine his volume ever being completely replaced. The value in Yoshino's book lies chiefly in its more up-to-date presentation style, its condensation of the results of more recent observational studies and its revelation of the considerable amount of investigational work on local climate undertaken in Japan, not formerly accessible because of the language barrier.

J. S. HOPKINS

The structure of turbulent shear flow (second edition) by A. A. Townsend. 230 mm × 170 mm, pp. xi + 429, *illus.*, Cambridge University Press, Bentley House, 200 Euston Road, London NW1 2DB, 1975. Price: £15.50.

This second edition of Townsend's well-known book is a complete revision of the original monograph, which was published in 1956, and comparison with the previous edition is inevitable. The current edition covers material up to about 1973, and the enormous amount of work on turbulent shear flows in the intervening years is evidenced by the increased length of the bibliography. The book itself is more than 100 pages longer, and contains a completely new chapter on turbulent convection. The author describes many modern theories of turbulent flows, and assumes familiarity with the basic ideas and mathematics of fluid mechanics, so the book is most likely to be of use in postgraduate research.

Some of the additional pages are due to a more detailed derivation of the basic equations and general properties of turbulent flow. The first four chapters give a clear description of such statistical quantities as correlation functions and energy spectra, and how they are related to the structure of the flow. The development of a field of turbulence under very simple external conditions is also presented here, and it is a pity that, while most of the initial sections are very thorough, the treatment of the so-called 'rapid-distortion' theory is somewhat hurried. This theory, which describes the response of a turbulent fluid to a rapid strain is one of the few analytic theories which really predict the structure of the turbulence, and is well supported by experimental results. As such, the results of the theory are often used elsewhere in the book to provide some physical foundation for semi-empirical flow calculations. The description of rapid distortion is more complete in the first edition, and two figures, 3·9 and 3·10, are simply reproduced from the first edition without defining anywhere in the text the quantities plotted.

The rest of the book is devoted to particular types of flow, namely pipe and channel flow, free turbulent flow, boundary layers and wall jets, turbulent convection, and curved streamline flow. These chapter subjects are the same as the first edition, with the exception of the chapter on convection. They all consist of a number of fairly short sections, and describe a very large amount of experimental and theoretical work. Together with the full bibliography, this makes the book very valuable as a reference work, although difficulties with notation and a few confusing misprints may possibly cause problems in one or two isolated cases.

There are a number of meteorological applications in the book, in spite of there being only five pages describing the turbulent Ekman layer. The atmospheric surface layer, or constant-stress layer, is discussed in the general context of turbulent wall layers, and the sections concerned with the dynamical effects of heat have many applications in meteorology and oceanography. A great deal of work from the fields of geophysics, engineering, and aerodynamics is brought together in this book, and presented in a way that brings out the basic similarities and underlying structures of the flows.

The author succeeds in giving the reader some real feeling for what a turbulent fluid looks like and how it behaves in various circumstances. Some understanding of the structure of the flow is necessary before useful semi-empirical theories can be developed, and many such models are analysed in terms of their underlying assumptions, the justification for the assumptions, and also their limitations. The presentation of the mathematical models is mostly very lucid, and gives an insight into the process involved in constructing an empirical theory. Anyone concerned with the theory of turbulence in the atmospheric boundary layer would certainly find the book illuminating and useful.

R. I. SYKES

OBITUARY

It is with regret that we have to announce the death of Mr F. W. Ward, Senior Scientific Officer, Preston, on 3 December 1975.

CORRECTIONS

Meteorological Magazine, January 1976, p. 27, Figure 1. The labelling of the axes implies that decreases of temperature and humidity with increasing height correspond to negative lapse rates, which is incorrect; the signs of the numbers labelling both axes should therefore be reversed.

Meteorological Magazine, February 1976, p. 64. The eighth line from the foot of the page should read 'or within -3σ to -2σ of Ratcliffe's mean value of 510 dam . . . '.

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked 'For Meteorological Magazine'.

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THE METEOROLOGICAL MAGAZINE

Vol. 105, No. 1246, May 1976

MR ERNEST GOLD, C.B., D.S.O., O.B.E., F.R.S.

With the passing of Mr Ernest Gold on 30 January at the age of 94, meteorology lost one of its outstanding figures, the Royal Society its senior Fellow, and the Meteorological Office a former second-in-command who dominated the scene for a quarter of a century.

After a brilliant career in mathematics and physics at St John's College, Cambridge, Gold joined the Meteorological Office in 1906 only to return to Cambridge the following year as Schuster Reader in Dynamical Meteorology at the tender age of 26. It was during the next three years that he published his historic explanation of the newly discovered stratosphere in terms of radiative equilibrium involving both water vapour and ozone. Another of his early papers, published in 1908, on barometric gradient and wind force is also a classic. These outstanding contributions were recognized by his election to the Royal Society in 1918 at the early age of 37.

In 1910 Gold relinquished his Readership and returned to the Meteorological Office where he remained until his retirement in 1947. During those 37 years his influence and example on both the national and international scene were immense. In the First World War he commanded the contingent of meteorologists with the British Forces in France and emerged as Lieutenant-Colonel Gold, decorated with the D.S.O. and O.B.E. For the next 20 years, as Assistant Director, he was largely responsible for building up a forecasting service to meet the rapidly growing requirements of aviation and played a leading role in putting synoptic meteorology on a firm international basis. As President of the Commission for Synoptic Weather Information of the International Meteorological Organization (IMO) from 1920 to 1947 he probably did more than anyone else to organize an efficient world-wide system for the collection, coding and exchange of meteorological observations. He was also President of the Meteorological Sub-commission of the International Commission for Aerial Navigation from 1922 to 1946 and a member of three other IMO Commissions. His outstanding services to international meteorology were fittingly recognized by the award of the International Meteorological Organization Gold Medal and Prize in 1958. His scientific contributions were further acknowledged by the Symons Memorial Gold Medal of the Royal Meteorological Society of which he was President in 1934–35.

During the Second World War Mr Gold, as Deputy Director of a greatly expanded Meteorological Office, carried a heavy responsibility for providing meteorological services for the British Forces throughout the world. His

knowledge and experience, and his firm adherence to scientific principles ensured that the technical standards of British military meteorology were unrivalled. These contributions were recognized by the award of the Companionship of the Bath in 1942 and the American Medal of Freedom with Silver Palms in 1946.

Gold's was a very strong personality, revered and perhaps a little feared by his subordinates who could never be sure that the slightest error would escape his eagle eye. His stream of personal memoranda and instructions on all aspects of weather forecasting are still indelibly printed on the minds of the dwindling band of recipients who survive their originator.

When I first met Mr Gold he was already retired from public service but I shall always remember his abiding enthusiasm for the subject and his kindness and encouragement to me as a young man. I can see him now in the front row at meetings of the Royal Meteorological Society, apparently asleep, but rising to his feet, hand on hip, to put a sharp, pertinent question to a brash young scientist and complaining 'But, Mr President, Dr . . . has not answered my question. What I wanted to know was this. . .'. At one of his last public appearances, at a lecture by an Apollo astronaut at the Royal Society, he delighted the audience by saying that he wished he could have been on the Moon a few days earlier when he had fallen out of a pear tree and could have wished for a substantial reduction in the gravitational force! He was indomitable and kept his enthusiasm for meteorology and his impish sense of humour to the end.

B. J. MASON

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THE QUASI-BIENNIAL OSCILLATION IN TROPICAL STRATOSPHERIC WINDS: A METHOD OF FORECASTING

By B. N. PARKER

SUMMARY

Wind data for Canton Island and Gan at 30 and 50 mb are used to show a significant tendency for some events in the tropical stratosphere to occur near a particular time of year. Tests on linear regressions of the length of a period on the number of the month in which it began also show a significant relationship. Linear regressions of the rate of downward transmission of events from 30 to 50 mb on the month of the 30-mb event and of the lag between temperature and wind events on the month of the wind events are presented. A method of forecasting future cycles is described.

The oscillation in the zonal wind component which is most marked between 30 and 50 mb near the equator is one of the surprises of modern meteorology, in that before its discovery (Ebdon (1960) and Reed (1960) produced papers at about the same time) there was no prediction of its existence on dynamical grounds. This might perhaps lead one to assume that there is no necessity to take notice of it in general forecasting procedures or, in particular, in building numerical models of the general circulation, on the presumption that it has no discernible effect on the state of the rest of the global atmosphere. That this assumption is unwarranted may be gathered from Böhme (1969), Godson (1964),

Kats (1964) and Ebdon (1972 and 1975). In particular the Ebdon (1975) paper produces convincing relationships between the phase of this oscillation and the latitude of the maximum zonal wind speed at 500 mb—a factor which strongly influences the weather over wide areas, and in particular affects summers in the United Kingdom.

These publications established an interest in what has come to be known as the quasi-biennial oscillation (QBO) and relationships from some of them (e.g. Ebdon (1972 and 1975) and Bugayev *et alii* (1972)) might provide useful tools for forecasting the weather for the United Kingdom and Russia over extended periods if one had the necessary knowledge of future phases of the QBO.

To this end a study was initiated which used as basic data the monthly mean wind velocity at Canton Island (2° 46′S, 171° 43′W) from October 1953 to August 1967 and at Gan (0° 41′S, 73° 09′E) from September 1967 to May 1975. From these values the mean zonal wind component, $\bar{u}$, was computed for each month. The date of change-over from westerly to easterly was defined as the first month of easterly and that from easterly to westerly as the first month of westerly, and the dates of four events were extracted for each cycle: maximum westerly component ($D_{W\max}$), westerly to easterly change-over (D_{W-E}), maximum easterly component ($D_{E\max}$) and easterly to westerly change-over (D_{E-W}). At this stage histograms of frequency of occurrence of events in each month were plotted, and from these Table I was derived. It demonstrates the tendency for events to occur at a given time of year. At 30 mb, 16 change-overs occurred in the period January–June and only 3 in the remaining months July–December, whereas at 50 mb the downward transmission retarded the peak to 16 in April–September, leaving 3 in October–March. It is difficult to establish in these circumstances which particular statistical test is appropriate. Owing to the cyclic form of the data the Kolmogorov–Smirnov one-sample test does not apply and it would appear that despite Siegel (1956), this is one instance in which the chi-square test fits the requirements better. The chi-square test was used to measure the difference between the observed distribution of dates on which events occurred and a random distribution which was assumed to be an equal number in each four-monthly period. The results show the distribution of 50-mb and 30-mb change-overs to be significantly different at the 1 per cent level from an equal number in each four-monthly period. The maxima are not so highly organized, perhaps because there is at times some difficulty in dating them accurately, and at 50 mb their distribution is not significantly different from random. At 30 mb, however, the 5 per cent level is attained.

There is then a strong basis for supposing that some events tend to occur near a given time of year and it was thought possible that a variation in the date of an event might affect the length of the interval between it and subsequent events. As a first step towards investigating this hypothesis a series of scatter diagrams was plotted, each relating the month in which an event occurred to the length of the following cycle, half-cycle, phase or arc (see Table II for definitions of these terms).

Figure 1 shows the scatter diagram for the increasing westerly arc at 30 mb and it may be seen that the points cluster in the early part of the year with intervals of moderate length, but those arcs starting in June and August were very short, hinting at a trend for decreasing arc lengths with later dates of commencement.

TABLE I—PREFERENCE OF STRATOSPHERIC EVENTS AT CANTON ISLAND (OCTOBER 1953 TO AUGUST 1967) AND AT GAN (SEPTEMBER 1967 TO MAY 1975) FOR OCCURRING AT A PARTICULAR TIME OF YEAR.

Months in which event occurred	D_{W-E}		D_{E-W}		either change-over		χ^2		Significance level	
	Number of change-overs									
	30 mb	50 mb	30 mb	50 mb	30 mb	50 mb	30 mb	50 mb	30 mb	50 mb
Jan.–Apr.	6	1	7	2	13	3				
May–Aug.	2	7	2	6	4	13				
Sept.–Dec.	1	2	1	1	2	3				
							10·8	10·5	1%	1%
	D_{Wmax}		D_{Emax}		either maximum					
	Number of maxima									
	30 mb	50 mb	30 mb	50 mb	30 mb	50 mb	30 mb	50 mb	30 mb	50 mb
Jan.–Apr.	0	1	1	4	1	5				
May–Aug.	6	7	3	2	9	9				
Sept.–Dec.	3	2	6	3	9	5				
							6·7	1·7	5%	—

TABLE II—DEFINITIONS OF TERMS USED TO DESCRIBE PORTIONS OF A CYCLE IN TROPICAL STRATOSPHERIC WINDS.

Interval		From	To	Schematic shape
1. Whole cycle	(a)	D_{E-W}	D_{E-W}	
	(b)	$D_{W\,max}$	$D_{W\,max}$	
	(c)	D_{W-E}	D_{W-E}	
	(d)	$D_{E\,max}$	$D_{E\,max}$	
2. Phase				
(a) westerly		D_{E-W}	D_{W-E}	
(b) easterly		D_{W-E}	D_{E-W}	
3. Half-cycle				
(a) westerly to easterly		$D_{W\,max}$	$D_{E\,max}$	
(b) easterly to westerly		$D_{E\,max}$	$D_{W\,max}$	
4. Arc				
(a) decreasing westerly		$D_{W\,max}$	D_{W-E}	
(b) increasing easterly		D_{W-E}	$D_{E\,max}$	
(c) decreasing easterly		$D_{E\,max}$	D_{E-W}	
(d) increasing westerly		D_{E-W}	$D_{W\,max}$	

Note. The illustrative diagrams in the final column follow the conventions used throughout; 'westerly' means *from* the west, and is plotted as positive. The horizontal lines represent zero $\bar{u}$.

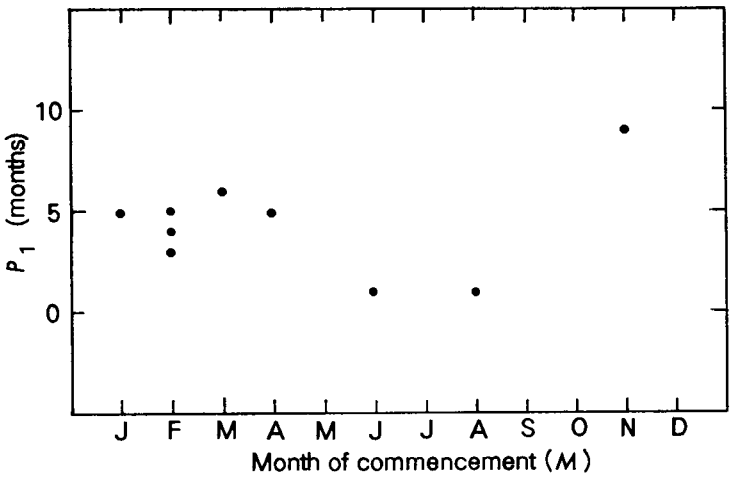

FIGURE 1—SCATTER DIAGRAM SHOWING LENGTH (P_1) OF THE INCREASING WESTERLY ARC AT 30 mb OVER CANTON ISLAND AND GAN AS A FUNCTION OF THE MONTH OF COMMENCEMENT

However, the arc which started in November lasted longer than any of the others and hence it may be said that arc lengths tend to decrease as dates of commencement vary from November to August. Figure 2 shows the scatter diagram rearranged to centre round January instead of round July. The rearranged months of commencement were then coded as 1–12 or 13–24 and a regression equation of arc length (P_1) on month-number of commencement (M) was formed. This was $P_1 = -0{\cdot}78\ M + 16{\cdot}0$, and the correlation between P_1 and M was found to be $-0{\cdot}84$, which 'Student's' t-test showed to be significant at the 1 per cent level. Figure 2 also shows the regression line and the 99 per cent confidence limits for it.

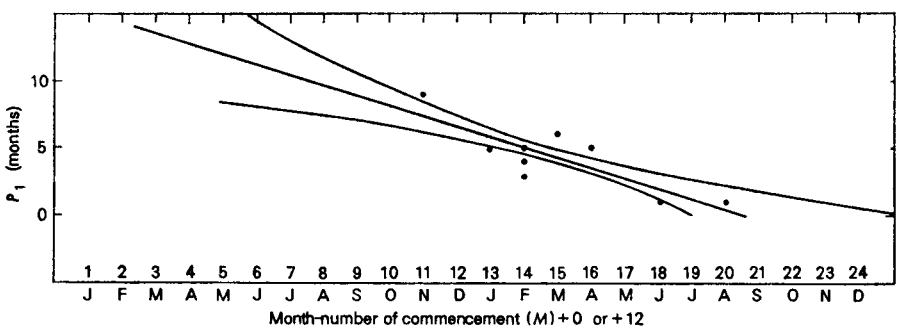

FIGURE 2—MODIFIED VERSION OF FIGURE 1 WITH MONTHS REARRANGED TO CENTRE ROUND JANUARY INSTEAD OF JULY

The regression line for $P_1 = -0{\cdot}78\ M + 16{\cdot}0$ is shown together with the 99% confidence limits.

The next part of the procedure was to replot the scatter diagram in January-to-December format and superimpose the regression line (Figure 3). Then the standard error of estimate S_p was determined by using the relationship $S_p = \sigma_p \sqrt{(1-r^2)}$, where σ_p is the standard deviation of the values of P_1, and r is the correlation coefficient between P_1 and M. Lines in Figure 3 showing twice the standard error of estimate can be assumed to envelop 95 per cent of the observations. Since the regression line from Figure 2 now appeared twice on Figure 3, a second (and in two cases a third) intercept was computed to define it fully, although of course the slope and first intercept remained the same.

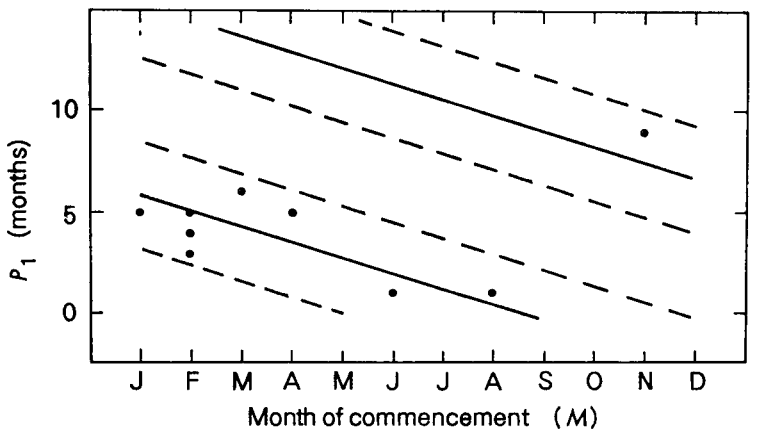

FIGURE 3—FIGURE 1 WITH SUPERIMPOSED REGRESSION LINE FOR $P_1 = -0{\cdot}78\,M + 16{\cdot}0$ SHOWN AS A FULL LINE

Dashed lines indicate standard error of the estimate (significant at the 1 per cent level by *t*-test).

These processes were repeated for all intervals to be considered and the results may be seen in Table III. In two of the intervals there is no usable relationship between P_1 and M, but in the majority it does appear that a regression line of slope slightly less than $-1{\cdot}0$ provides a reasonable explanation of the distribution, if the projection of the line beyond one December, or sometimes two Decembers, is accepted.

The same method was also used to prepare diagrams of the relationship between the month-number in which an event occurs at 30 mb and the number of months by which the same event at 50 mb lags behind it. It is interesting to note that variations have occurred in the past from the usually accepted figure for the downward transmission of events of 1–2 km per month (Ebdon (1963) and Böhme (1969)). The time taken for the change from westerly to easterly, for instance, to propagate from 30 to 50 mb varied between 2 and 12 months—a rate of between about 0·3 and 1·5 km per month. It seems possible that Table IV may be of more assistance in predicting dates of 50-mb events than the value of 1–2 km per month, at least for the change-overs and D_{wmax}, which are significant at the 0·1 per cent level by application of the *t*-test.

The investigation thus far has dealt with the QBO in the monthly mean zonal wind component. The QBO may also be traced in the temperature anomalies

at the same levels, although the month-to-month variability is much greater than that of the wind component. However, an inspection of the data showed that dates of change-over from negative to positive and positive to negative anomaly, and (to a smaller extent) of maximum positive and maximum negative anomaly

TABLE III—RELATIONSHIP BETWEEN THE LENGTH OF A PERIOD (P_1) AND THE NUMBER OF THE MONTH IN WHICH IT BEGAN (M)

	Interval	m	c_1	c_2	c_3	Standard error of estimates *months*	r	Significance level *per cent*
30 mb		−0·78	16·0	6·7	—	1·3	−0·84	1
		−0·80	23·2	13·6	—	1·8	−0·84	1
		−0·47	14·9	8·4	—	1·4	−0·81	1
		−0·88	32·7	22·2	—	1·9	−0·89	1
		−0·63	15·5	8·0	—	1·3	−0·73	5
		−0·88	25·1	14·6	—	1·9	−0·79	2
		−0·75	24·1	15·1	—	1·9	−0·77	2
		−0·92	38·6	27·5	—	2·1	−0·87	1
		−0·89	37·5	26·9	—	1·9	−0·90	1
		−0·96	42·5	31·0	—	1·7	−0·93	0·1
		−0·82	43·1	33·3	—	2·1	−0·83	1
50 mb		−0·69	14·9	6·6	—	0·9	−0·97	0·1
		−0·84	17·2	7·2	—	1·5	−0·91	0·1
		−0·28	10·7	7·4	—	0·9	−0·86	1
		−0·31	8·0	4·3	—	0·6	−0·80	1
		−0·58	23·4	16·5	9·5	0·8	−0·99	0·1
		−0·65	15·7	7·9	—	0·8	−0·96	0·1
		−0·88	29·2	18·7	—	1·4	−0·94	0·1
		−0·92	40·9	29·9	—	1·8	−0·91	1
		−0·89	41·4	30·7	—	1·4	−0·94	0·1
		−0·84	40·1	30·0	19·9	1·6	−0·96	0·1
		−0·74	35·6	26·8	—	2·2	−0·83	1

m, c_1, c_2 and c_3 refer to the regression equation $P_1 = mM + c$, with c_1, c_2, c_3 being the values appropriate to the separate portions of the regression line (see Figure 3 and text). The equations for the increasing westerly arc at 30 mb are thus $P_1 = -0{\cdot}78\ M + 16{\cdot}0$ and $P_1 = -0{\cdot}78\ M + 6{\cdot}7$, and the equations for the 95% confidence limits for the first of these are $P_1 = -0{\cdot}78\ M + 16{\cdot}0 \pm (1{\cdot}3 \times 2)$. The correlation coefficient r and the significance level from 'Student's' t-test are also shown.

could be selected in a reasonably objective manner. The histograms of occurrence in each month (not reproduced here) showed a tendency to favour one half-year in preference to the other, as did those for the zonal wind component, and this was taken as an indication that a relationship between the month in which a temperature event occurred and the number of months later that the accociated wind event took place might be established. To assist in the examination of this relationship a further set of scatter diagrams was plotted. Negative-to-positive (− to +) temperature changes were taken to be associated with the following wind changes from easterly to westerly, and so on.

Much the same procedures used for the wind events were followed for temperatures, and Table V gives details of the results obtained, where D_{max+} and D_{max-} are the dates of occurrence of maximum positive and maximum negative temperature anomaly.

At 50 mb the relationship between D_{wmax} and D_{max+} appears to be useful ('Student's' t-test gives 0·1 per cent probability), and at 30 mb the relationships between D_{wmax} and D_{max+}, D_{Emax} and D_{max-} and between D_{W-E} and $D_{+ \text{ to } -}$ all seem to be worthy of consideration, with t-test probabilities of 1·0, 0·1 and 0·1 per cent respectively.

Diagrams constructed from Tables III, IV and V being given, the procedure for producing a forecast of the dates of future events is very simple. Suppose that it is desired to estimate dates of events for a whole cycle. The method adopted is to use the dates of the preceding 30-mb events (at cycle, half-cycle, phase or arc intervals before the event that one wishes to forecast) and, from the diagram for Table III, to estimate the length of the period appropriate to the month of commencement. This will give a range of likely dates which may be used in the arc forecast of the next event and the phase or half-cycle forecast of the one after that. Inconsistencies between estimates of the date of a particular event arrived at from three different intervals are eliminated before proceeding to the next date, greater weight being given to the more reliable relationships. The diagram for Table V may then be used to narrow the range of dates further for some of the events.

When the 30-mb forecasts are completed the same process is applied to the 50-mb data, and here one may also use the diagram for Table IV for all events except the occurrence of maximum easterly component, E_{max}, again adjusting towards the more significant results.

By using an earlier variant of this method a forecast was made in October 1973 of the dates of the events in the next cycle, and Figure 4 shows the results of this so far. At 50 mb the dates of the change-overs were accurately forecast within what for most purposes would be an acceptably small range. The value of D_{Emax} was badly in error but the associated zonal wind component was only some 5 kn stronger than a secondary maximum which occurred in the middle of the forecast range.

At 30 mb the zonal component changed from westerly to easterly much earlier than expected, and even a subsequent hesitation in the weak easterlies did not really allow the suggestion that this forecast was anything but a failure. The value of D_{Emax} and in particular the value of D_{E-W}, however, were well predicted, even though the range of dates expected was larger than one could wish.

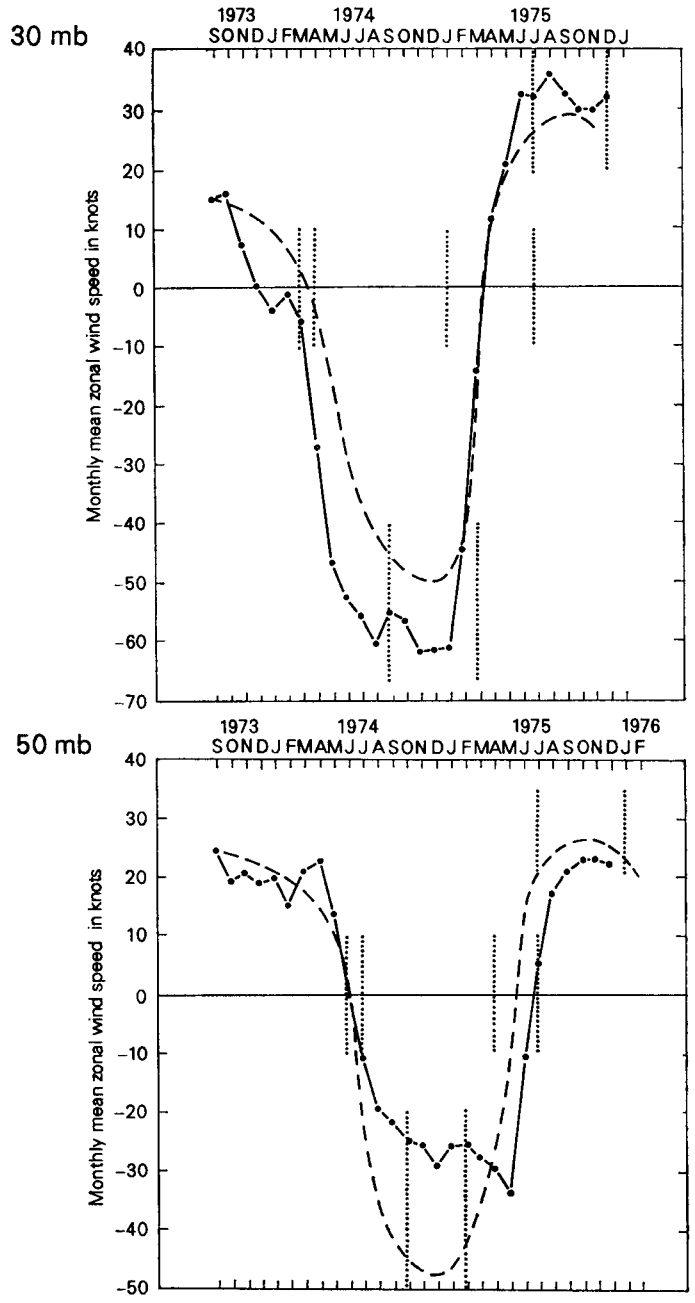

FIGURE 4—FORECAST AND ACTUAL DATES OF CHANGE-OVER AND D_{Emax} AND D_{Wmax} FOR GAN FOR 30 mb AND 50 mb

·——· actual dates – – – forecast dates

The forecast was made in October 1973 and produced times of events delineated by a range of months shown as vertical dotted lines. The forecast curve (– – –) was then added to show clearly the expected sense of the change, with no attempt to predict actual values. Positive values of zonal wind speed denote westerliness and negative values easterliness.

TABLE IV—RELATIONSHIP BETWEEN THE MONTH IN WHICH AN EVENT OCCURS AT 30 mb (M) AND THE NUMBER OF MONTHS LATER THAT A SIMILAR EVENT OCCURS AT 50 mb (P_2)

Event	m	c_1	c_2	Standard error of estimate *months*	r	Significance level
W_{max}	−0·76	15·5	6·3	1·4	−0·95	0·1%
W–E change-over	−0·78	16·1	6·8	1·1	−0·90	0·1%
E–W change-over	−0·22	6·1	3·5	0·3	−0·90	0·1%

See Table III for explanation of symbols.

TABLE V—RELATIONSHIP BETWEEN THE NUMBER OF MONTHS (P_3) BY WHICH WIND EVENTS LAG BEHIND TEMPERATURE EVENTS, AND THE MONTH OF THE TEMPERATURE EVENT (M)

Zonal-wind event	Temperature-anomaly event	m	c_1	c_2	Standard error of estimate *months*	r	Significance level
50 mb W_{max}	max+	−0·67	14·4	6·4	1·2	−0·94	0·1%
30 mb W_{max}	max+	−0·82	16·4	6·6	1·9	−0·82	1%
E_{max}	max−	−0·59	15·7	8·7	1·2	−0·93	0·1%
W–E change-over	+ to −	−0·80	12·7	3·1	1·7	−0·90	0·1%

See Table III for explanation of symbols.

Of six verified results, then, only one was totally unacceptable, one was marginally so and four were good.

It is suggested that the relations between dates of events in the stratosphere at Gan and lengths of subsequent intervals may serve as a basis for forecasting dates of events up to a cycle in the future. The forecast need not apply exclusively to Canton Island and Gan, since Böhme (1969) states unequivocally (para 2.1.1) that 'independently of longitude each phase (e.g. the westerly-wind maximum) occurs simultaneously at a given height and latitude'.

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551.501.796:551.575.5(427)

ACOUSTIC SOUNDING OF A SEA FOG

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SUMMARY

The appearance of a spring sea fog on the record of an acoustic sounder situated near the north-west coast of England is discussed speculatively in terms of atmospheric mechanisms in and above the fog layer. Acoustic and visual evidence for the presence of convection in the fog layer is mentioned, as is acoustic evidence for the presence of a neutrally buoyant region in the upper part of the layer, and a dynamic though statically stable layer above.

In the early afternoon of 5 March 1975 a bank of sea fog rolled inland from the Irish Sea over an acoustic sounder operating beside Lancaster University. Although many examples of acoustic-sounder records have been published while the technique has become established over a period of seven years (for example, McAllister *et alii*, 1969 and Bean *et alii*, 1973) we have been unable to find any reports associated explicitly with foggy conditions, though we would guess that there must have been fog in some of the cases of strong nocturnal cooling (Wyckoff, Beran and Hall, 1973); however, even if the latter were foggy, such layers chilled from beneath were statically stable. By contrast in the present case there is some evidence that the fog was in a statically neutral or even unstable layer bounded above by a pronounced stable layer. If this was the case then the situation is similar in many respects to the mainly cloud-free convecting layer beneath the subsidence inversion of an anticyclone, though on a much reduced vertical scale.

The acoustic sounder was sited 73 metres above mean sea level and 9 km east of a flat coast, and consisted of two adjacent antennae, each having a 1·5-m diameter fibre-glass paraboloidal reflector with a horn-loaded public-address speaker at the focus. The antennae acted as separate transmitter and receiver

but were sufficiently close to one another to be described as a 'monostatic'* system. At the 1000-Hz operating frequency the half-power beam width was 20°, the receiver sensitivity 100 mV Pa^{-1}, and the acoustic power output 20 W in the pulses. Pulse-repetition frequencies were 0·5 and 0·2 Hz, and the pulse length was 40 ms. The maximum receiver gain was 140 dB.

Patterns of echo strength, corrected for inverse-square effect by a range-gain compensator, and displayed on a time–height graph, are shown in Figure 1, and discussed briefly in this note. Two points should be borne in mind throughout: (1) theory (Monin, 1962) and observation strongly suggest that a monostatic acoustic sounder detects echoes from volumes of air containing turbulently

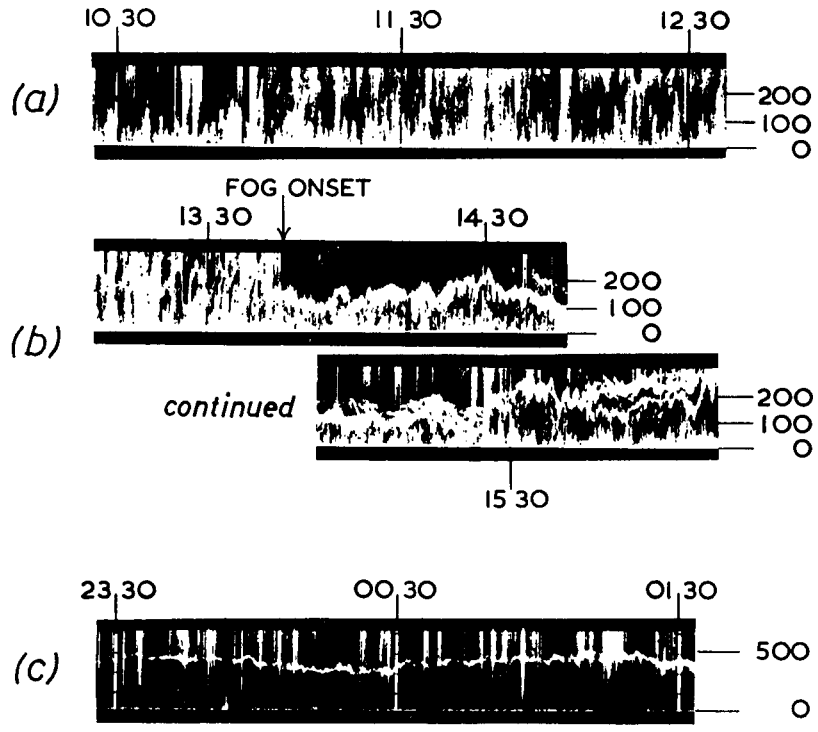

FIGURE 1—ECHO STRENGTHS AT LANCASTER ON 5–6 MARCH 1975

Signal (and noise) are white, silence is black.
Height (ordinate) is marked in metres above the sounder.
Time (abscissa) is marked in Greenwich Mean Time.
Station co-ordinates: 54°N, 2°45′W, height 73 m above m.s.l.

**monostatic:* a word used by workers in this field to describe a system in which transmitter and receiver either share the same antenna or are placed in such close juxtaposition that they can be regarded as being effectively in the same place; otherwise the system is described as *bistatic.* (Both words appear to have been invented by someone ignorant of Greek; *monotopic* and *ditopic* might be better for the purpose (Editor).)

induced temperature inhomogeneities on the scale of half the wavelength of the probing signal (15 cm in this case), and that such echoes are many orders of magnitude stronger than those to be expected from water droplets typical of fog or cloud (Little, 1972). Therefore the patterns in Figure 1 relate to the temperature field, and only in an indirect way to the presence of fog droplets. (2) spikes of 'echo' extending down from the top of the sounder record (most obvious in Figure 1(c)) represent noise, probably from the nearby motorway, which is enhanced with increasing height by the range-gain compensator.

Figure 1(a) shows echo patterns recorded by the Lancaster sounder on the morning of 5 March 1975, that is to say before the arrival of the fog. Mostly clear skies allowed strong solar heating to produce an unstable (superadiabatic) layer close to the ground in a north-westerly flow from the sea about 9 km away. Although some 50 km south-south-east of the sounder, the noon radiosonde ascent from Aughton near Ormskirk (Figure 2) penetrated a similar airflow and showed that the first 14 mb (about 140 m) of the atmosphere had a superadiabatic lapse rate. The 'tufts' of echo apparent in Figure 1(a), extending upwards from near the surface to heights varying between 60 and 200 m, are typical of sounder records obtained in convection from the surface, which have been shown (Beran, Little and Willmarth, 1971) to represent plumes of rising, thermally inhomogenous air.

At about 1330 GMT visibility at the sounder began to deteriorate; the site was enveloped by swirling fog at 1340 and in the following half hour temperatures at screen level and at 30 m fell by 2 deg. Figure 1(b) shows that the echo pattern on the sounder record changes strikingly at about 1340 GMT; echo tufts are replaced by a fairly uniform 'grass' apparently contained beneath a reflecting layer centred at about 150 m, a height which agrees well with visual estimates of the top of the patchy fog. From the detailed appearance of the sounder record (which has not copied well from the film original) we believe that the grass represents convective elements with horizontal dimensions much smaller than the 600 m typical of pre-fog conditions (calculated on the assumption that plumes etc. have been moving with the wind at the 3-m level, where the speed remained close to 5 m/s for much of the day). Visual observations from ground level of the patchiness of the fog, and its occasionally broken and hummocky upper surface, further suggest the presence of some type of convection. This could have been produced by residual static instability in the cool fog layer as it overran the previously warmed surface, or it might have been maintained mechanically in a nearly but not exactly neutrally stable fog layer.

From many reports (McAllister *et alii*, 1969) it is well established that a horizontally continuous reflecting layer, such as that centred at 150 m in Figure 1(b), corresponds to a pronounced stable layer. Just such a layer was apparent between 140 m and 460 m above Aughton at 12 GMT (Figure 2) but it is clear from Figure 1(b) that though there is evidence of a weakly defined layer between heights of 100 and 200 m at Lancaster before 1340 GMT, this layer strengthened, lowered, and steadied with the arrival of the fog beneath. The mechanism of this change is obscure, and presumably involves effects localized in the north Irish Sea and surrounding land which produced the sea fog (that is to say, which produced the cool saturated layer beneath the stable layer), as well as larger-scale events maintaining the stable layer itself—notably subsidence in a weak ridge ahead of a warm front advancing from the west. The virtual absence of echo from higher levels is to be expected, since the stable layer inhibits the upward

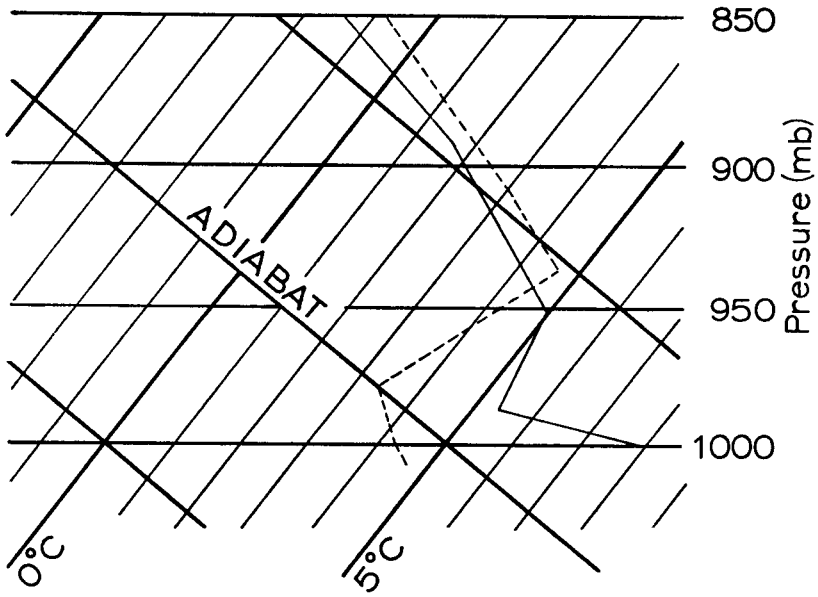

FIGURE 2—TEMPERATURE SOUNDINGS FROM AUGHTON DISPLAYED ON A TEPHIGRAM

Solid line 12 GMT, 5 March 1975.
Dashed line 00 GMT, 6 March 1975.
Station co-ordinates: 53° 33′N, 2° 55′W, height 59 m above m.s.l.

extension of turbulence generated in lower layers, but the sharpness of the upper boundary at the reflecting layer (i.e. of the population of temperature inhomogeneities) cannot be explained in simple terms; it is probably related to the production of turbulence by shear instability within the stable layer, and is evidence of structure on a vertical scale smaller than that of the stable layer itself. Such structure has been investigated by radar (Browning, Starr and Whyman, 1973) and further acoustic evidence is discussed below.

At 1540 GMT the fog became much more patchy and the sun began to break through quite frequently. Figure 1(b) shows that the reflecting layer began to lift at about the same time, subsequently varying about the 200-m level in occasionally obvious concert with the now more clearly visible plumes underneath. The echo-free layer between the plume tops and the stable layer, apparent in much of the afternoon's record, is consistent with volumes of relatively warm air rising and overshooting through a region in which they are neutrally buoyant. At about 1600 GMT the reflecting layer split into two layers separated by an echo-free layer some 40 m deep. This accords with radar observations cited above (which refer to anticyclonic subsidence inversions overlying convective layers) and the recently proposed theory (Pellacani, C. and Lupini, R., unpublished) that gravity waves trapped in a stable layer capping a convective layer can grow by resonance with convective perturbations until they break down into layers of turbulence localized in the upper and lower levels of the stable layer.

After the period covered by Figure 1(b) the reflecting layer rose slowly, reaching a height of about 400 m by midnight (Figure 1(c)). This is consistent

with the midnight sounding from Aughton (Figure 2), remembering the considerable separation of sites, and with the approach of the warm front. The reflecting layer was still pronounced, and since there were no underlying plumes, this suggests that at least a substantial part of the acoustically effective turbulence in the stable layer throughout the day was not produced by overshooting plumes, the source being presumably shearing instability of some type.

ACKNOWLEDGEMENTS

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551.508.53

AN IMPROVED WIND-DIRECTION INDICATOR

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SUMMARY

A wind-direction indicator has been constructed which has better damping response than an indicator of conventional design and is thus capable of producing more precise wind-direction data.

1. INTRODUCTION

The conventional wind-direction indicator has a vane which aligns itself with the wind direction by pivoting about a vertical axis. Standard meteorological patterns have shortcomings, particularly with regard to their dynamic characteristics (Giblett *et alii*, 1932). For many applications an approximate indication of wind direction may be acceptable, but it was considered that in experiments to determine relationships between wind and its effects on the ventilation system of livestock buildings, wind direction would be an important factor and its accurate measurement essential.

The relevant characteristics of a wind-direction indicator are:

(a) *Frequency response.* This will determine the speed with which it will move to a new equilibrium position in response to a shift in wind direction.

(b) *Damping.* This is essential so that any oscillatory tendencies are quelled in a predictable manner. In the design to be described particular importance is assigned to damping.

(c) *Angular resolution.* The equilibrium angular position of the indicator should always be the same as the wind direction within defined limits and furthermore this change should be registered by any associated recording apparatus.

(d) *Sensitivity.* This is the minimum wind speed necessary to move the indicator to the equilibrium position. Some standard angular deviation (usually 90°) is chosen for the initial condition.

(e) *Directional bias.* This could arise from asymmetrical construction aerodynamically or from imbalance about the pivotal axis. The latter would manifest itself if the indicator had not been correctly levelled.

(f) *Pivotal friction.* Pivotal friction could be regarded as contributory to damping, lack of angular resolution and lack of sensitivity, but it is listed here because it is fairly easy to identify and can be regarded separately as a problem of mechanical design.

2. THEORY

Mathematical expressions for the motion of a wind-direction indicator have been given (Giblett *et alii*, 1932; MacCready and Jex, 1964) but it can be shown quite easily that the criterion for critical damping or for over-damping is

$$\frac{Ka^2}{4u^2} \geqslant 1, \qquad (1)$$

where $K = (abc/I)\,(dc/d\alpha)\,(\rho u^2/2)$ and

a,b,c, = length of rod, vane height, vane width respectively,

$dc/d\alpha$ = rate of change of lift coefficient with angle,

I = moment of inertia,

ρ = air density, and

u = wind speed.

The moment of inertia, I_1, of the vane only is

$$I_1 = \frac{b\sigma}{3}\left[3a^2c + \frac{c^3}{4}\right], \quad .. \quad .. \quad .. \quad .. \quad (2)$$

where σ is the surface density of the vane.

The first moment T_1 of the vane is

$$T_1 = abc\sigma. \quad .. \quad .. \quad .. \quad .. \quad .. \quad .. \quad (3)$$

This is counterbalanced (usually) by a mass M on a rod of length l. Thus the first moment T_2 of the counterbalance mass is

$$T_2 = Ml. \quad .. \quad .. \quad .. \quad .. \quad .. \quad .. \quad (4)$$

The moment of inertia of the counterbalance mass is

$$I_2 = Ml^2. \quad .. \quad .. \quad .. \quad .. \quad .. \quad .. \quad (5)$$

If the effects of any support rod are neglected, then from equations (3) and (4)

$$M = \frac{abc\sigma}{l}, \quad .. \quad .. \quad .. \quad .. \quad .. \quad .. \quad (6)$$

whence from equation (5)

$$I_2 = abc\sigma l \quad .. \quad .. \quad .. \quad .. \quad .. \quad (7)$$

and the total moment of inertia is

$$I = I_1 + I_2 = \frac{b\sigma}{3}\left[3a^2c + \frac{c^3}{4}\right] + abc\sigma l. \quad .. \quad (8)$$

Some numerical values can now be taken into account. Putting $\rho = 1{\cdot}22$ kg/m^3, using the following expression for $dc/d\alpha$ (Royal Aeronautical Society, 1970)

$$dc/d\alpha = (0{\cdot}34\, b/c) + 2{\cdot}25, \quad .. \quad .. \quad .. \quad .. \quad (9)$$

and choosing $l = a/4$, then expression (1) becomes

$$\left[0{\cdot}34\,\frac{b}{c} + 2{\cdot}25\right] a \geqslant \left[8{\cdot}20 + 0{\cdot}55\,\frac{c^2}{a^2}\right]\sigma. \quad .. \quad .. \quad (10)$$

Now the highest value of the ratio b/c that can effectively alter $dc/d\alpha$ is about 20. Expression (10) then becomes

$$a \geqslant \left[0{\cdot}91 + 0{\cdot}06\,\frac{c^2}{a}\right]\sigma. \quad .. \quad .. \quad .. \quad .. \quad (11)$$

A light-alloy vane is unlikely to have a surface density of much less than 2 kg/m^2. Thus if c is negligible, expression (11) shows that $a \geqslant 1{\cdot}8$ m. It would therefore appear that provided that the ratio b/c is about 20 the device should be well damped whatever the values of b or c when the length of the support rod is about 2 m.

Abandonment of the counterbalance mass and using expressions (1) and (2) yields a similar criterion ($a \geqslant 1{\cdot}44$ m). Thus the counterbalance mass would appear not to alter the design greatly but it obviates directional bias due to faulty levelling and also distributes the load more uniformly on the central bearing. Aerodynamic effects of counterbalance weights have been considered in detail (MacCready and Jex, 1964) but it was considered that in the present context these would be small and could be neglected. There is probably some advantage in not achieving critical damping, but rather to have one extra overshoot in response to a stepwise change in wind direction, because this involves less time in settling to equilibrium. This would also enable the support rod to be shortened somewhat. In the design to be described it was found that the rod could be shortened considerably while retaining acceptable damping characteristics.

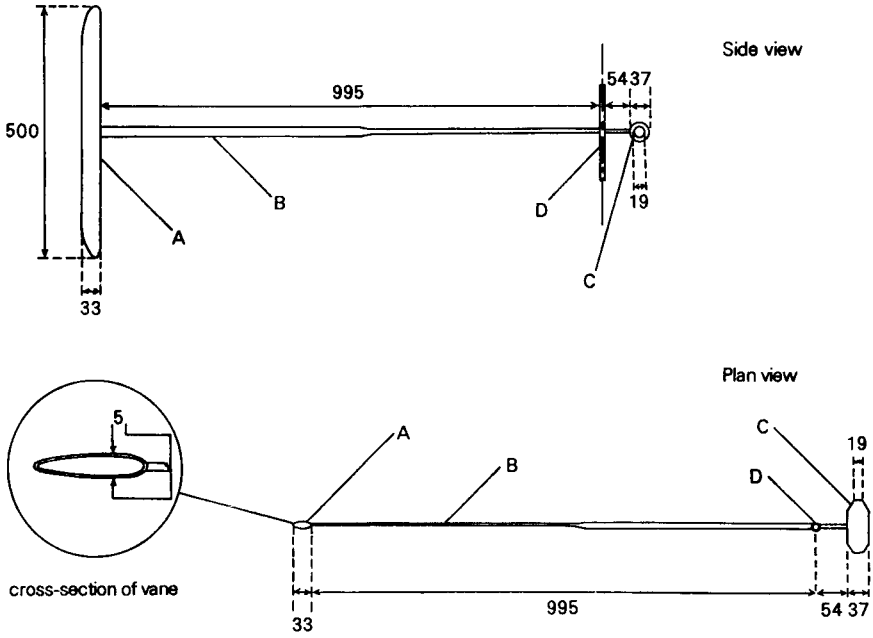

FIGURE 1—SIDE AND PLAN VIEWS OF EXPERIMENTAL WIND INDICATOR

(See text for explanation of letters A–D.)

3. Description

A wind-direction indicator as shown in Figure 1 was constructed in the light of the criteria outlined above. The essential steps in the process were:

(a) The vane (A) was constructed by almost flattening a tubular aluminium extrusion of approximately 0·51-mm wall thickness, trimming the ends as shown to make them curved, and finally sealing the tube by welding.

(b) The vane was glued with epoxy resin to the support rod (B) which was also made from an extruded aluminium tube of 0·51-mm wall thickness. About half-way between the axis of rotation and the vane the support rod was slightly flattened, the flattening increasing towards the vane.

(c) The weight of the vane was counterbalanced by a brass weight (C) machined to a cylindrical shape and mounted on the aluminium tube.

(d) The central shaft (D) was arranged to rotate in a bearing protected by an aluminium housing (not shown) which also contained a potentiometer connected to the shaft.

The design as described could only be implemented because the particular aluminium extruded sections were available; previously tubes with such thin walls were available commercially only as rolled tubes, which have a lower strength.

4. Tests

The wind indicator was tested together with a Meteorological Office Mk III direction indicator in the laboratory and out of doors. In the laboratory test the wind indicators were set up in an airstream and released from a deflexion angle of 30° in such a way that they resumed their alignment with the direction of the airstream. The angular deflexion at any instant during this process was determined from high-speed recorder charts of the voltage across the potentiometer. Refinements in the design were achieved progressively by modification followed by tests to produce the indicator shown in Figure 1. The sensitivity of the indicator was assessed by releasing it from a deflexion of 90°.

In the out-of-doors test both instruments were at a height of 5 m. Their angular movements were recorded by a chart recorder in the laboratory. In addition the behaviour of both indicators in relation to that of smoke plumes generated upstream was observed visually.

5. Results

It was found that the tendency of the indicator to overshoot was reduced as the vane was flattened. Since the purpose of using tubular materials for the vane was to provide rigidity in planes normal to the vane it could not be made entirely flat. The partial flattening of the support tube near to the vane had an observable effect as had the shaping of the ends of the vane. A satisfactory compromise between position and weight of the balance weight was found empirically. Smaller weights further from the pivot were shown to affect the performance adversely by increasing the moment of inertia, whereas larger weights closer to the pivot became cumbersome. In an original version the weight was in the form of a massive tube similar in shape and size to that shown in Figure 1, but

threaded over the support rod. A definite improvement was achieved by fixing it at right angles to the support rod, thereby concentrating its mass with respect to its distance from the axis, thus reducing its moment of inertia.

The result of a typical laboratory test on the final version of the indicator is shown graphically in Figure 2, together with the results for the Mk III indicator. It can be seen from Figure 2 that the experimental indicator was less than critically damped, giving one overshoot, whereas the Mk III indicator exhibits at least four overshoots beyond the equilibrium position. Also the experimental indicator finally reaches the equilibrium position within 2·5 seconds. The Mk III indicator is still oscillating after 6 seconds. Equation (1) shows that the condition for critical damping is independent of wind speed. This point was not investigated for the experimental indicator owing to limitations of the laboratory apparatus. However, only one overshoot was observed at all wind speeds lower than 3·8 m/s. Although the theory is strictly applicable only to small deflexion angles (Mazzarella, 1972) the observed behaviour of the indicator suggests that it can be used as an effective guide to design. The rather large initial deflexion angle of 30° was chosen to illustrate the ability of the indicator tor each equilibrium quickly. The comparison with the Mk III indicator is tentative; the latter may be preferable at higher speeds and for prolonged exposure in rough conditions. The results for out-of-doors comparisons are mentioned but briefly

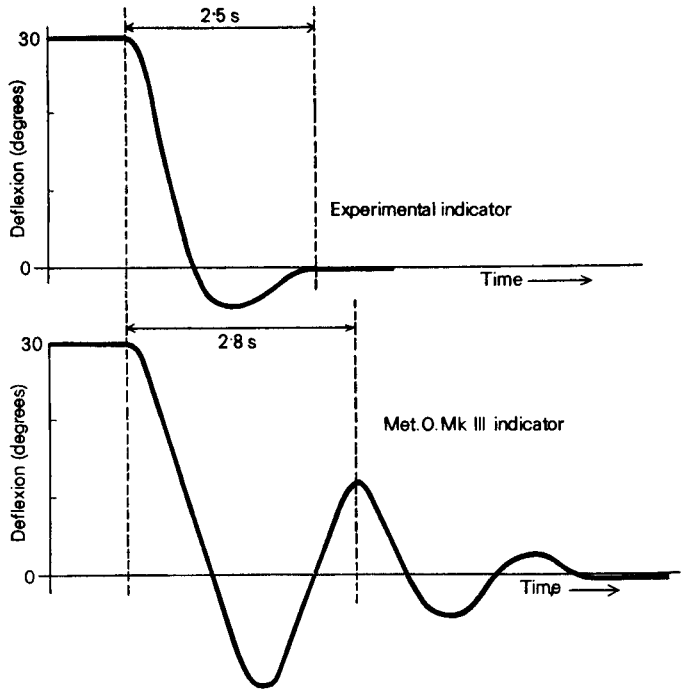

FIGURE 2—RESPONSE OF EXPERIMENTAL INDICATOR AND METEROLOGICAL OFFICE Mk III DIRECTION INDICATOR IN LABORATORY

Air speed 3·8 m/s.

since they raise questions that are outside the intended scope of this report. However, it was observed that a smoke plume typically adopted a serpentine form as it was caught up in areas of wind turbulence, and that the movements of the experimental direction indicator followed the contortions of the smoke plume much more faithfully than did those of the Mk III indicator. Thus the more frequent excursions of the chart record for the former were taken as a better indication of wind behaviour than the record for the Mk III indicator.

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THE NORTH-EAST MONSOON AND THE CAUSES OF THE WINTER RAINS OF SOUTH-EAST INDIA

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SUMMARY

Examination of meridional sea-level pressure profiles over India, the Atlantic and Pacific and of winter rainfall over India and Sri Lanka demonstrates that the so-called north-east monsoon over south-east India differs little, either in wind or in weather, from the generality of the northern-hemisphere trade winds.

1. INTRODUCTION

It is often mentioned that the winter rains of south-east India are due to the north-east monsoon. Though the winter monsoon is originally dry, it is supposed to acquire enough moisture before blowing over the eastern parts of peninsular India because of its travel over the Bay of Bengal. Gaspar (1962), in the introductory remarks to his study of the rains over Madras State, associated these rains with the north-east monsoon. Thiruvengadathan (1965) proposed different types of upper-air flow patterns as being responsible for spells of strong and weak north-east monsoon conditions defined in terms of the rain. The concept of a north-east monsoon over south India is thus not only accepted but its characteristics are being studied, much on the lines of the rainy south-west monsoon.

The word 'monsoon' was originally used for the 180° change in direction of the prevailing winds over the Arabian Sea from winter to summer and vice versa. During summer the sea-level circulation over Asia, particularly in the

southern region, is dominated by the heat low centred over Arabia and north-west India. In winter, however, the Siberian anticyclone dominates the circulation over Asia. These pressure- and wind-systems, which are the result of differential heating of land and sea, have been accepted as accounting for the monsoonal phenomena over India and surrounding areas.

Flohn (1960) suggested that the monsoonal kind of wind changes observed in the tropics and subtropics can also occur on a completely land-covered globe owing to the seasonal variation of the solar radiation. He concluded that the physical causes of monsoonal winds are to be found not only in the differential heating of land and sea but also in the thermally controlled seasonal migration of the planetary pressure- and wind-belts in the continental sections of the globe.

It later became customary to call the prevailing wind in summer the 'summer monsoon' and that in winter the 'winter monsoon'. The summer monsoon in India, because of its rain-bearing nature, has suffered a complete shift in its meaning, and is now used for the associated rains. A 'weak monsoon' thus means scanty rainfall over the country, and an 'active monsoon' means widespread heavy rainfalls. This usage, however, has gradually started to spread to the winter north-east monsoon, as has previously been stated. This trend in the shift of the meaning of 'monsoon' has engendered a misconception that the winter north-easterlies over south India are very different from the north-east trades over the rest of the tropics. The following observations show the contrary to be the case.

2. Meridional pressure profiles

The meridional sea-level pressure profiles for January along 80°E over India and along 105°E, which passes through the centre of the Siberian anticyclone, and two more, one through the mid Atlantic and the other over the Pacific, are presented in Figure 1. These profiles are prepared from the hemispherical charts given by Godske *et alii* (1957). The profiles over both the oceans show similar characteristics. The maxima at 30°N correspond with the subtropical high-pressure belt, and the minima at 55°N and 60°N over the Pacific and Atlantic with the Aleutian and Icelandic lows respectively. The pressure in the subtropical ridge over the Atlantic is greater than that in the Pacific by about 6 mb. In the equatorial regions a similar difference, but of magnitude 3·5 mb, is present. Consequently the Atlantic trade on the average could be stronger than its Pacific counterpart. An estimate of the average strength of the trade wind in the Atlantic in the latitude belt 10°–20°N can be made from Figure 1, assuming balanced motion among the pressure-gradient, Coriolis, and frictional forces. The frictional force was incorporated in the calculations by assuming an angle of 30° between the wind and the isobars, and the trade-wind strength came to about 8 m/s. A similar calculation for the Pacific winds gave a strength of 5·3 m/s. These values agree fairly well with those obtained by Riehl (1954) from actual wind values, which lends support to the accuracy of the pressure profiles presented in Figure 1. While the pressures in the Atlantic are higher than those in the Pacific at the corresponding latitudes, the pressure difference in the subtropical ridge is greater than at any lower latitude. This shows that the subtropical anticyclone in the Atlantic is somewhat more intense than its counterpart in the Pacific.

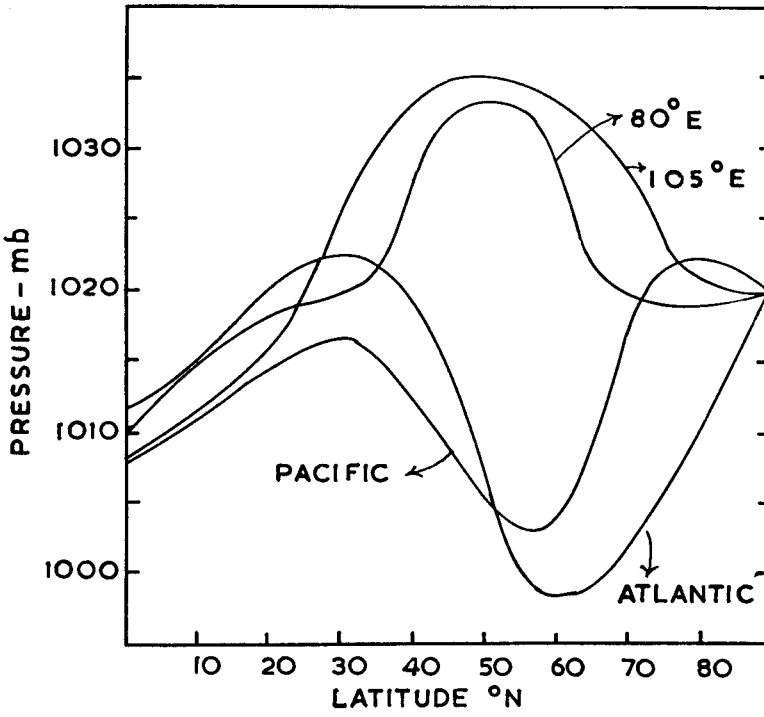

FIGURE 1—MERIDIONAL PRESSURE PROFILES

The pressure profiles along 80°E and 105°E show maxima at latitude 50°N which are due to the Siberian anticyclone. The subtropical ridge at 105°E is completely masked by the continental high. However, at 80°E the subtropical ridge is revealed by the inflexion of the curve at 30°N. South of 20°N both the curves run more or less parallel to the profiles over the oceans, and the resulting winds cannot differ much from those over the oceans. The effect of the continental high is practically confined to latitudes north of 20°N. It is apparent that in the vicinity of longitude 105°E easterly flow occurs instead of the usual westerlies in the latitude band 30°–50°N. It is therefore proper to consider these easterlies as the winter monsoon, but the easterlies south of 20°N may not be treated as being different from the trades.

3. Rainfall over south peninsular India

The mean monthly rainfall amounts (September to February) at some of the stations on the east coat of peninsular India and Sri Lanka expressed as percentages of the annual rainfall are presented in Table I. Maximum rainfall at Visakhapatnam occurs in the month of October and it shifts to Pamban in November and to Trincomalee in December. The trend of the values indicates that the maximum should be further south of Trincomalee in January and February. The gradual shifting of the heaviest rainfall to the south, from October to February, and the simultaneous southward movement of the equatorial

TABLE I—MEAN MONTHLY RAINFALL EXPRESSED AS A PERCENTAGE OF THE ANNUAL RAINFALL

		Sept.	Oct.	Nov.	Dec.	Jan.	Feb.
Visakhapatnam	(18°N)	16·8	26·4	8·8	1·6	0·8	1·6
Madras	(13°N)	8·8	20·8	24·0	12·0	1·6	0·5
Pamban	(9·5°N)	1·6	18·4	32·0	20·0	7·2	1·6
Trincomalee	(7·5°N)	4·8	12·8	20·0	20·8	12·8	5·6

trough in this area as shown by the charts prepared by Frost and Stephenson,* which are reproduced here in Figure 2, clearly indicate that the rainfall during these months is due to the activity in the equatorial trough. Furthermore, if the so-called north-east monsoon is responsible for the rains over the Coromandel coast, the rains should be at a maximum in December and January when the north-east wind regime reaches its peak. Thus the climatological aspects of rainfall also do not accord with the view that the winter rains over the coast of Madras are due to the north-east monsoon.

The daily precipitation and sea-level pressure at some stations on the east coast and the synoptic charts of the area for the three winters 1963–65 have been examined by the author in order to make a further enquiry into the nature of winter precipitation. The precipitation and pressure variations at Madras and Trincomalee for the period 15 November 1963 to 31 January 1964 are presented in Figure 3 as an example; the precipitation is shown to have occurred when the pressures were low. The high rainfall and low pressures during the beginning of the period were due to westward-moving low-pressure systems. In the first week of December there was a cyclonic storm which moved close to the peninsular coast and then recurved to east-north-east. This gave considerable rain at Madras. Between 21 and 26 December the pressures were low, but there was no rain at Madras. During this time again there was an easterly wave in the south which gave considerable rainfall farther south over the Indian coast and Sri Lanka. In January there was no rainfall at all at Madras, and the pressure was more or less steady. Occasional precipitation occurred, however, at Trincomalee. This means that as the season advanced the synoptic systems that develop in the equatorial trough gradually receded to the south.

A correlation study between pressures at Madras and at some stations in central and northern India gave high positive correlations. This shows that the low-pressure systems in the vicinity of Madras which gave rain to that area are also associated with lower pressures over the northern parts of the country but not with the intensification of the anticyclone in that region.

4. Conclusions

The meridional pressure profile in winter over India south of 20°N is similar to those over the Atlantic and Pacific and therefore the north-easterlies over India are similar to the trade winds.

The winter rainfall over the Coromandel coast is associated with the equatorial trough, and the disturbances in the equatorial trough and the adjoining easterlies.

*FROST, R. and STEPHENSON, P. M.; Meteorology of Malaya. (Unpublished, copy available in the Meteorological Office Library, Bracknell, Berks.)

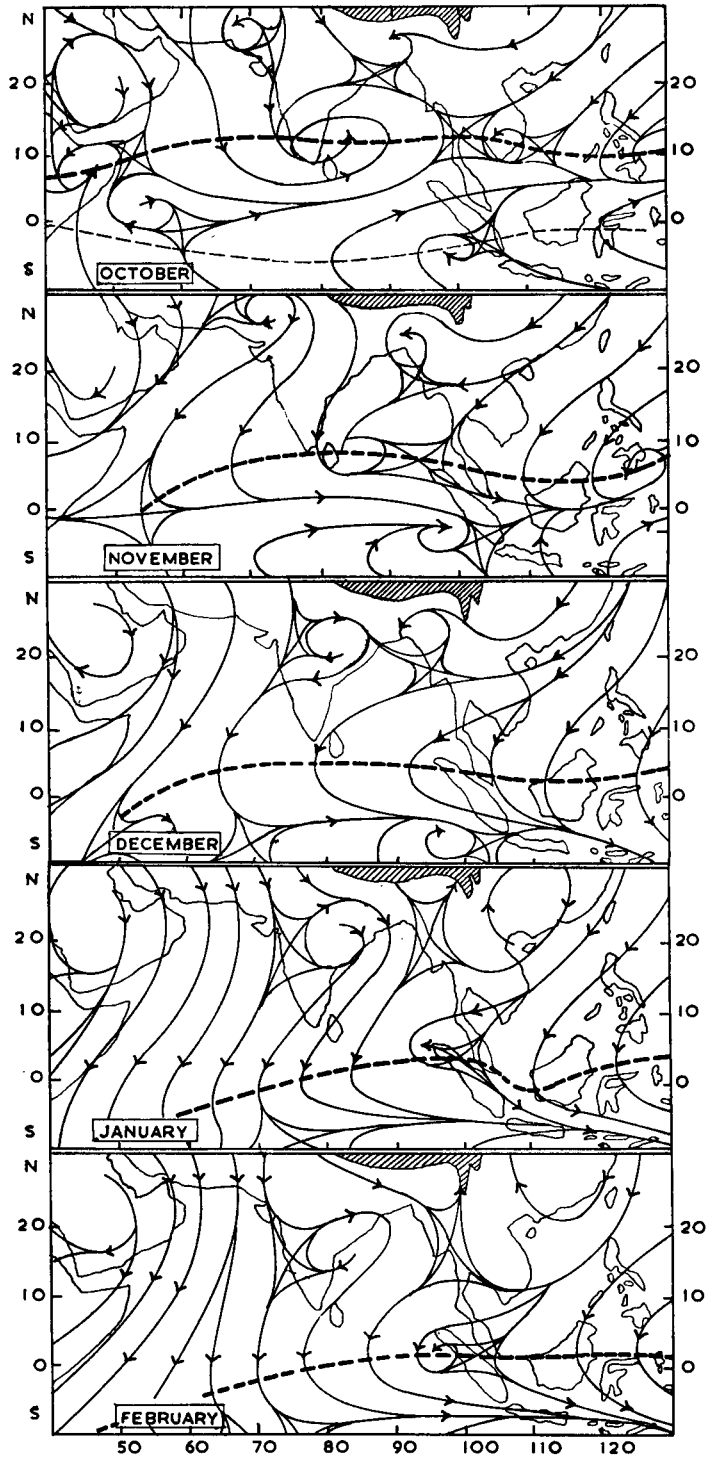

FIGURE 2—3000-ft STREAMLINE CHARTS
Dashed lines indicate equatorial troughs. (After Frost, R. and Stephenson, P. M.)

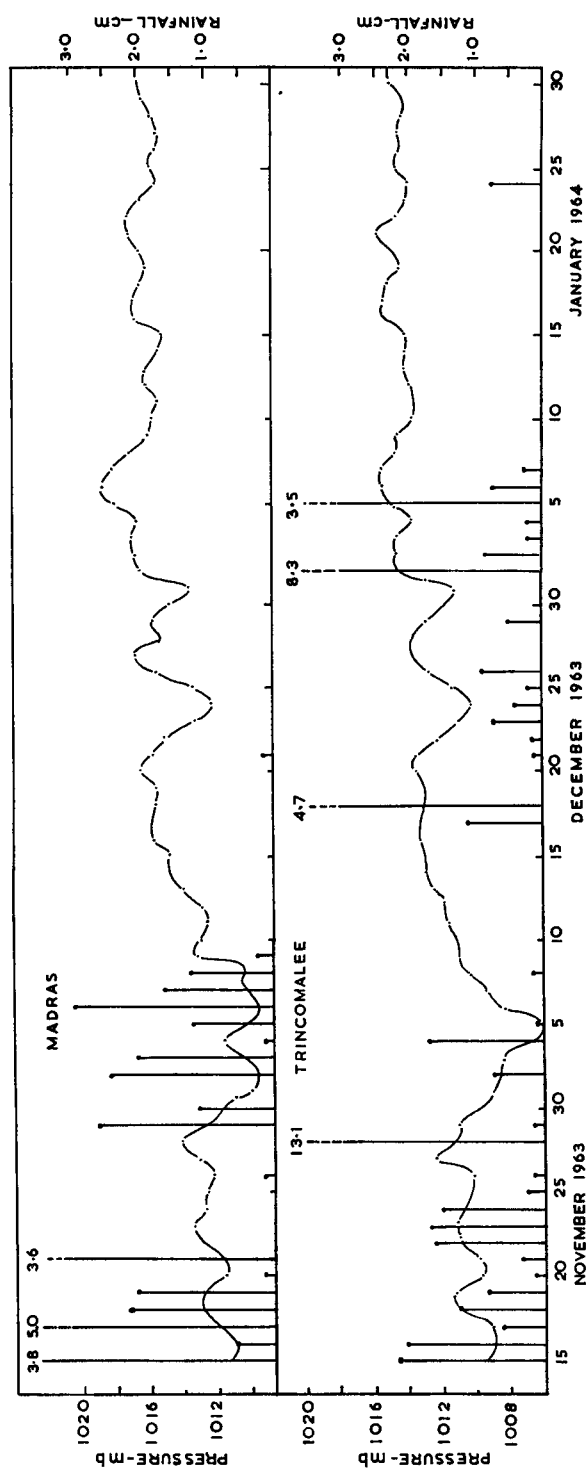

FIGURE 3—PRESSURE AND RAINFALL VARIATIONS AT MADRAS AND TRINCOMALEE, 15 NOVEMBER 1963–31 JANUARY 1964

Thus the so-called north-east monsoon over south-east India differs little, either in wind or in weather, from the trade wind as the latter is generally known and understood.

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LETTER TO THE EDITOR

Weather-spell frequencies and mathematical models

The following notes are prompted by the publication in the *Meteorological Magazine* of 'An investigation into spells of wet and dry days by region and season for Great Britain'.*

Throughout this investigation it is clear that there are difficulties in fitting the various models to frequencies of longer spells, and these results are summarized in the author's Conclusion by the statement that 'the models give only a rough guide to the occurrence of infrequent long spells'. The mathematical reason for this lack of agreement is that all the models used imply a positive persistence ($P_{(r+1)}/P_r$ increasing) whereas, in reality and except under perfectly constant conditions, spells must reach a stage where negative persistence (or anti-persistence) occurs.

*BLAIR-FISH, J. A.; An investigation into spells of wet and dry days by region and season for Great Britain. *Met Mag, London*, **104**, 1975, pp. 360–375.

The graphically illustrated results show that negative persistence is present in the data used, for example, with wet spells at Cwm Dyli. In the Meteorological Office discussion on 'Thirty-day forecasting' (1955) Jenkinson states that anti-persistence occurs in weather spells of 15–30 days. A detailed study of runs of dry days over south-west, south-east and east England (Lawrence, 1957) shows that, during the season from June to August, persistence is positive for spells up to 8–10 days, zero or slight for spells of from 8 to 10 days to about 30 days and from then on negative. Belasco (1948) found that, for the British Isles, the probability that the next day will be anticyclonic after a run of anticyclonic days increases slightly in the range 3–20 days and thereafter shows a marked decrease.

For abnormally long spells of wet and dry weather at the several British stations examined, Newnham (1916) states that the persistence is doubtful. Persistence must depend on the regional climate (Lawrence, 1954), for example on whether the rainfall is predominantly of a showery or of an intermittent type. In more temperate regions, persistence is related to the characteristic trends of the particular season and year in question, and, for example, in an unusually dry year, negative persistence in dry-spell frequencies may not occur until spells have reached abnormal lengths. On the other hand, negative persistence could occur as a result of a weather singularity; for example, at Kew, wet early Junes tend to be followed by dry or fairly dry late Junes, a phenomenon occurring in some eight years during the period from 1871 to 1964 (Lawrence, 1965).

The concept of persistence is of basic importance in meterology because it provides a practical and comprehensible parameter or set of parameters which indicate significant differences between regions, seasons, weather regimes, spell-length etc. for various definitions of spell. Thus no model can be entirely satisfactory unless it incorporates a realistic pattern of persistence.

Further attention may be usefully given to mathematical models which allow for negative persistence, particularly with reference to infrequent longer spells but greater progress might be made from a world-wide study of the natural variation of persistence. The resulting more numerous and significant universally defined constants of persistence could be applied practically to achieve more accurate objective descriptions of climate.

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NOTES AND NEWS

European Centre for Medium-range Weather Forecasts

The newest international organization for meteorology, the European Centre for Medium-range Weather Forecasts (ECMWF) attained independent existence on 1 November 1975 when its Convention came into force. The Council, composed of representatives of the 13 States which had so far ratified, met from 4 to 6 November. Besides necessary initial formal business, the Council confirmed Dr Wiin-Nielsen as Director of the Centre, and decided on the maximum expenditures both for 1976 and for the first five years. The Headquarters Agreement with the United Kingdom, defining the Centre's legal status in the UK and the headquarters building to be provided by the UK, was also signed.

North Atlantic Ocean Stations Scheme

At the WMO informal planning meeting held in Geneva in February 1975 to produce a revised telecommunication plan for the new North Atlantic Ocean Stations (NAOS) Scheme, it was agreed that an objective should be to operate the meteorological communications by radio-teleprinter (RTT) rather than by wireless telegraphy (morse). Because of various factors, including technical compatibility of equipment, and radio-propagation problems over the North Atlantic region, it was agreed that first a series of exploratory trials would be conducted between the Russian, French and Norwegian vessels and the Bracknell shore station. These trials took place between mid September and mid December 1975. Reports on the trials are now being compiled by the participating bodies.

Meteorological effects of stratospheric aircraft

The three years' research program of the Committee on Meteorological Effects of Stratospheric Aircraft (COMESA) has been concluded and a detailed report will be produced in the near future. The results of the work indicate that the currently planned operations of Concorde aircraft in the stratosphere are not likely to result in effects on the ozone content of the atmosphere or on the climate which could be distinguished from natural variations.

Earlier calculations on the production of nitrogen oxides by heating in the shock waves associated with nuclear explosions have now been extended to include the contribution due to mixing between the hot fireball and the ambient air as the fireball rises in the atmosphere. This has been achieved by modifying a numerical model of cumulonimbus cloud to represent the nuclear cloud. The resultant findings confirm that massive amounts of NO_x, equivalent to that expected from about 1000 Concordes flying regularly, were injected into the stratosphere in past nuclear weapon testing; these massive injections produced no detectable changes in global ozone.

Acoustic sounding at Cardington

An acoustic sounder has been built and put into operation at Cardington. The sounder emits a series of narrow-beam sound pulses and picks up any returns from sharp gradients in refractive index in the overlying atmosphere. These gradients may be due to rising thermals, convectively driven turbulence, gravity

waves, or a marked temperature increase often observed at the top of the boundary layer. The returns, observed by an array of microphones, are displayed to show the variations of temperature-gradient activity with height and time above the sounder. Up to the present one of the principal difficulties has been to deduce the magnitude of the gradients from the returns with any degree of accuracy. However, the Cardington team, working in conjunction with a team from the Department of Electronics and Electrical Engineering of University College, London, have recently compared the small-scale temperature gradients inferred from the sounder with those obtained by direct measurements made by a temperature probe on a tethered-balloon cable, measuring in essentially the same air as the sounder, in both unstable and stable conditions; the agreement has proved remarkably good. Profiles of the vertical and horizontal wind speeds derived from acoustic Doppler measurements will be evaluated in a series of experiments to be carried out in the near future.

Retirement of Mr C. J. M. Aanensen

Conrad Aanensen retired from the Meteorological Office after nearly 39 years' service in March 1975—the last three-and-a-half years or so as a Higher Scientific Officer, in which capacity he had been re-engaged after stepping down on reaching the age of 61 from his Senior Principal Scientific Officer post as Head of the Meteorological Research Flight. His vitality and interest in meteorology were such that in these last three-and-a-half years he was first responsible for a valuable piece of research, namely the application of readings from the Oxford–Heriot-Watt satellite-borne radiometer on NIMBUS 4 to the construction of stratospheric charts, and later took a large part with the International Scientific Management Group in the planning of the aircraft program for the GARP Atlantic Tropical Experiment.

After graduating with high honours in Mathematics and Physics from the University of Wales he joined the Meteorological Office in 1936. He was soon forecasting at Croydon for Imperial Airways—the forerunner of BOAC, now the overseas division of British Airways, until the outbreak of the Second World War at which time there was a 'general post' within the Office, with some offices closing and others opening to serve the Royal Air Force. Aanensen found himself first at Bristol for a short time, then at Norwich for a year, followed by short spells at Gloucester and Bristol before joining the new upper-air section at Dunstable in 1943. He worked in the group dealing with radiosondes under the leadership of P. A. Sheppard, and remained associated with this work until brought down to earth on posting to Porton in 1949 to pursue research on the boundary layer—a subject close to the heart of the then Director and of his successor. He stayed at Porton for five years, gaining promotion to Principal Scientific Officer in 1950, and then joined the operational side of the Office for 12 years, successively at Bawtry and H.Q. Bomber Command. Promotion to Senior Principal Scientific Officer in 1966 saw him take charge of the Meteorological Research Flight, a post which used to the full his long experience and administrative abilities.

Many will miss his kindly interest and wish him well in his retirement, which will give him time perhaps to pursue the many practical hobbies in which he is expert.

R. F. JONES

Retirement of Mr E. J. Bell

Mr Eric J. Bell, C.Eng., F.I.E.E., Assistant Director (Telecommunications) retired from the Office on 12 April 1976 on reaching the age of 60 years. His career began in the Royal Air Force where he distinguished himself in a variety of posts and attained the rank of Squadron Leader before leaving the Service in 1945. There followed a couple of years in industry during which a highlight was the 1947 Royal Tour of South Africa when Mr Bell had special communications responsibilities aboard the Royal train.

Mr Bell entered the Office on 1 January 1948 as a Signals Officer at Dunstable and was promoted to Principal Signals Officer in 1957. During the 1950s he established himself as a key figure in the telecommunications centre and played an active part in the development and reorganization of the meteorological telecommunications system in the years following the war. The period saw an increase in the use of teleprinter circuits, both land-line and radio, into Europe and elsewhere, with a corresponding decline in the volume of data gathered by reception of morse radio broadcasts and also the introduction of facsimile as an important facility for the dissemination of pictorial products. Mr Bell was also heavily involved in the complicated move of the telecommunications centre from Dunstable to Bracknell in 1961, an undertaking which posed severe technical and organizational problems but which was carried through with remarkable smoothness.

Subsequently during the 1960s the international decision to provide a high-speed trunk circuit encircling the globe and to introduce faster automated methods within regions necessitated the planning of a long-term program of modernization and automation of the Bracknell telecommunications centre. It fell to Mr Bell, following his promotion to Superintending Grade Engineer in 1971 and appointment as Assistant Director (Telecommunications) to lead the effort required to bring these plans to fruition. The implementation of this ambitious program called for considerable drive and stamina. In 1972 additional turmoil and problems were created by the move of the telecommunications centre from the Napier Shaw Wing to the new Richardson Wing, but the operation was effected with minimal interruption of the Telecommunications Branch's services to the Office.

Throughout his career of more than 28 years' service in the Office Mr Bell has been a tireless and dedicated worker with a shrewd and professional approach which has earned him a deservedly high reputation. His job has necessarily involved him in a heavy schedule of international meetings where he has become widely known and respected for his negotiating skill, sound common sense and integrity. As the head of the Telecommunications Branch he has been an indefatigable defender of the interests of his branch and staff, but even when he was arguing a case most forcibly, good humour was never very far away; he leaves the branch in a very healthy state for his successor.

In retirement one cannot imagine Mr Bell subsiding into inactivity for some time to come and no doubt he will soon be applying his talents and energy to good purposes elsewhere.

We wish Mr and Mrs Bell all possible success, health and happiness in the future. May they enjoy many years of contented retirement!

G. A. CORBY

Retirement of Mr R. E. Farms

On 21 March 1976 Mr R. E. Farms retired from the Meteorological Office after a career of over 38 years which was spent largely in the provision of meteorological services for military and civil aviation in various posts at home and overseas.

He graduated from St Andrews University in 1937 in Physics and Mathematics and joined the Office in October 1937. Before his training at Kew and Croydon was complete he left in January 1938 to serve at Heliopolis in Egypt. In 1940 he went to Habbaniya in Iraq and was granted a commission in October 1941. He subsequently served at several places in East Africa and returned to the United Kingdom towards the end of 1943. After about six months at H.Q. No. 3 Bomber Group he went in mid 1944 to Supreme H.Q. Allied Expeditionary Force, where he worked with the late Dr J. M. Stagg on the meteorological preparations for the D-Day landings of the Allied Expeditionary Force in Europe. He subsequently served at 87 Group. At the end of the war after attaining the rank of Wing Commander he was demobilized and returned to the Office as a civilian in June 1946. He spent some months in M.O.6, the branch responsible for most RAF affairs in the UK, and also in the Meteorological Office Training School which was then located in Kingsway in central London. He subsequently joined the branch responsible for overseas routes outside Europe for a spell of duty with civil aviation. In 1951 he was promoted Principal Scientific Officer and went as a senior forecaster to Prestwick, where he stayed for rather more than nine years. In 1960 he moved to H.Q. Transport Command, Upavon as Chief Meteorological Officer, and remained there until he was promoted to Senior Principal Scientific Officer in January 1971. He then went to Heathrow and stayed there until his retirement.

Mr Farms has been concerned with operational meteorological work for almost the whole of his career. His practical approach to any problem and his concern for his staff have been immediately apparent to the many colleagues who have had the pleasure of working with him during a long career. When I met him in the autumn of 1937 soon after he joined the Office I soon had experience of his prowess as a golfer and his keenness for the game when we used to play on the course which surrounds Kew Observatory. He is still very keen and plays a very good game. His many friends will wish Bob Farms and his wife a long and happy retirement.

N. BRADBURY

OBITUARY

It is with regret that we record the death on 13 February 1976 of Mr A. E. Burtonshaw, Telecommunications Technical Officer II, MetO 16.

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked 'For Meteorological Magazine'.

The responsibility for facts and opinions expressed in the signed articles and letters published in this magazine rests with their respective authors.

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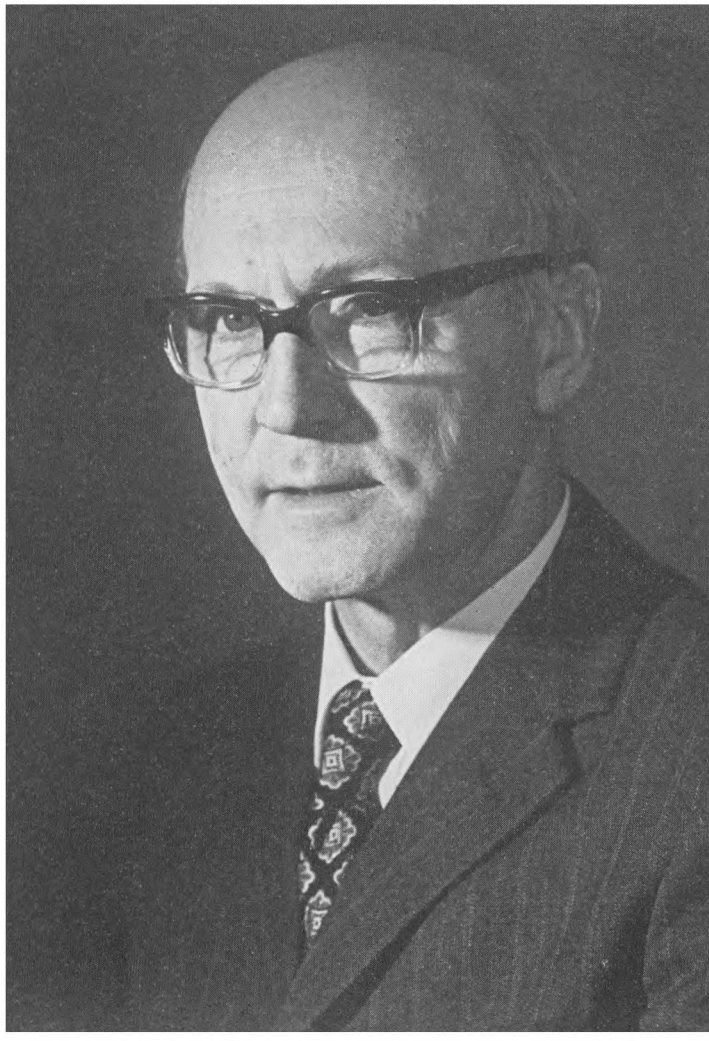

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MR J. K. BANNON, I.S.O.

METEOROLOGICAL OFFICE Met.O.893

THE METEOROLOGICAL MAGAZINE

Vol. 105, No. 1247, June 1976

RETIREMENT OF MR J. K. BANNON, I.S.O.

On the retirement of Mr J. K. Bannon as Director of Services on 26 April 1976 the Meteorological Office lost another of its major figures of the post-war era. In an outstanding career spanning 38 years John Bannon filled a wide variety of posts in both the Services and Research Directorates, to all of which he brought a high degree of dedication, professional ability, excellent judgment, and sound common sense, qualities that have been of immense service to the Office in a period of rapid change and modernization.

Educated at the Royal School, Armagh, he entered Emmanuel College, Cambridge in 1935 and graduated as a Wrangler in the Mathematical Tripos in 1938. Soon afterwards he joined the Meteorological Office as a Technical Officer, and, after a succession of forecasting posts at Mildenhall, Sullom Voe, Pembroke Dock, and H.Q. 93 Group, RAF, he was commissioned as a Flight Lieutenant, RAFVR, in 1943 and posted to H.Q. Bomber Command. In 1944 he was promoted Squadron Leader and served with the 2nd Tactical Air Force in Europe until the end of the war. Upon demobilization in 1946 he returned to the Meteorological Office as a Senior Scientific Officer in the General Research and Observatories Branch under A. C. Best, where he published a number of important and still-quoted papers on the estimation of large-scale vertical currents from rates of rainfall, on the humidity of the upper troposphere and lower stratosphere based on the pioneering frost-point hygrometer measurements of the Meteorological Research Flight, and on the incidence of severe turbulence at high altitudes. In 1952 he moved to the Upper Air Climatology Branch where he investigated the structure of the Middle East jet stream, and wrote important papers on the temperature structure of the troposphere and lower stratosphere (with A. Gilchrist), on stratospheric temperatures over the Antarctic, and on the flux of water vapour due to the mean winds over the northern hemisphere (with A. G. Matthewman and R. Murray). Well-deserved promotion to Assistant Director in charge of the Special Investigations Branch came in 1960.

Selection for the Imperial Defence College in 1963 pointed to further advancement and, after successive spells as Assistant Director for Aviation Services, for Public Services and for Observational Requirements and Practices, promotion to Deputy Director (Observational Services) followed in 1971. His services had been given public recognition in 1969, when he was appointed a Companion of the Imperial Service Order. In 1973 he succeeded Mr P. J. Meade as Director of Services with the rank of Under Secretary.

In this onerous post, by quiet and firm leadership and a realistic sense of priorities, he was able to meet unprecedented demands for both old and new services, partly by the smooth introduction of automatic methods but, above all, by securing the willing co-operation of his staff. His open-mindedness and ability to see the Services and Research Directorates as complementary rather than as rival parts of the same organization have brought them closer together than ever before.

His wise and courteous counsel and quiet good humour will be greatly missed, especially by those of us who have been privileged to work closely with him over the years.

I am sure that all John Bannon's friends and colleagues will wish to join me in wishing him, and Mrs Bannon, a long, active and happy retirement.

B. J. MASON

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AN ANALYSIS OF PRESSURE JUMPS AT LUQA, MALTA IN THE YEARS 1968–72

By J. D. PERRY

SUMMARY

Analysis of pressure jumps at Malta for a five-year period shows the maximum frequency to be associated with synoptic situations where an easterly airstream at the surface is separated from a potentially unstable layer in the middle troposphere by a marked inversion. These conditions are often accompanied by anomalous surface winds which may satisfy squall criteria. Severe low-level turbulence reported in these circumstances is discussed and there is an Appendix indicating the factors favourable to such developments, which present a particular hazard in that they may occur in clear air.

INTRODUCTION

Several reports of pressure jumps at Luqa have been published, notably by Lamb (1954) and Kirk (1961, 1963a–d), showing rapid changes of pressure of from one to two millibars which were associated with oscillatory surface-wind effects and thermogram discontinuities. A more recent occasion of pressure jumps which occurred at a time when severe low-level turbulence was being reported by aircraft which were landing at Luqa prompted this investigation of the phenomena, and an analysis of data for the five-year period from January 1968 to December 1972 showed that pressure jumps of two millibars or more were not uncommon. The conditions associated with these jumps were similar to those given by Hardy (1971) as a prerequisite for low-level turbulence in Cyprus.

DEFINITION OF PRESSURE JUMPS AND OF THEIR FREQUENCY

If a pressure jump is defined for the purpose of this investigation as a change in pressure of at least two millibars in a period not exceeding one hour, then during the five-year period from January 1968 to December 1972, 252 pressure jumps were recorded by the two barographs at Luqa, Malta. The jumps, both positive and negative, were equal to or in excess of 3 mb on 75 occasions, 4 mb on 20 occasions, and 5 mb on 4 occasions. This definition embraces

both sudden changes of pressure and steady but rapid changes of pressure which show in the routine observations as a pressure tendency of at least 6·0 mb in three hours. The sudden changes which comprise the majority of the data examined usually become obscured in the tendencies calculated for routine observations, while large but steady changes of pressure are much less frequent in the central Mediterranean area than they are in higher latitudes, and very few of the 252 pressure jumps fall in this category.

The annual frequency of pressure jumps is given in Table I below, and it is noteworthy that 1970 had remarkably fewer pressure jumps than the other years.

TABLE I—ANNUAL FREQUENCY OF PRESSURE JUMPS, 1968–72

	⩾ 2 mb	⩾ 3 mb	⩾ 4 mb	⩾ 5 mb
1968	57	18	4	0
1969	52	15	6	0
1970	29	7	0	0
1971	57	19	6	1
1972	57	16	4	3
Total	252	75	20	4

Frequently a sudden increase of pressure was followed by a fall, or vice versa. On some occasions the reversal of jump was delayed by several hours, while isolated jumps of pressure without recovery were not uncommon. Although the chance of a pressure jump occurring in any one hour is, on the basis of this study, less than 1 per cent, it is evident from examination of the barograph traces that the likelihood of a pressure jump increases significantly during periods when the trace is unsteady. Figure 1 shows the barograms for the period 24 July–6 August 1972 and it will be seen that the normal diurnal variation of pressure is disturbed on 30 and 31 July and again on 2 and 3 August. During these periods the traces became irregular with minor fluctuations of pressure before a series of significant pressure jumps. The jumps on 31 July occurred in rapid succession whereas the first two jumps on 2 and 3 August were separated by about six hours. The final jump on 3 August was a rapid fall immediately followed by a rise. If a sequence is defined as all those pressure jumps separated by less than three hours between jumps then the annual frequency decreases appreciably as shown in Table II.

TABLE II—ANNUAL FREQUENCY OF SEQUENCES OF JUMPS, 1968–72

	⩾ 2 mb	⩾ 3 mb	⩾ 4 mb	⩾ 5 mb
1968	33	11	2	0
1969	31	11	4	0
1970	18	7	0	0
1971	29	8	4	1
1972	35	10	4	3
Total	146	47	14	4

Frequency by month and time of day (GMT)

Table III shows the diurnal and monthly frequency distribution of pressure jumps for the five-year period from 1968 to 1972. It is evident from the table that pressure jumps are most likely during the period April–September and between the hours 2100 GMT and 0600 GMT. Examination of the barograms and relevant surface observations showed that this distribution was mainly attributable to periods of easterly surface winds at Luqa, Malta.

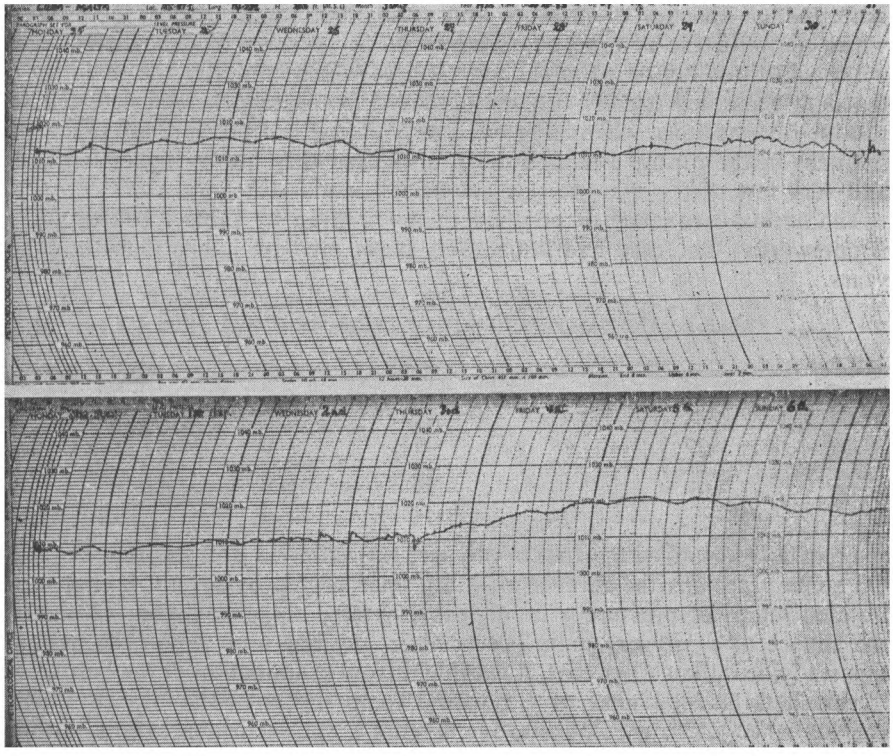


FIGURE I—BAROGRAPH RECORD AT LUQA, MALTA, 24 JULY–6 AUGUST 1972

TABLE III—FREQUENCY OF PRESSURE JUMPS BY MONTH AND TIME OF DAY, 1968–72

Time (GMT)	J	F	M	A	M	J	J	A	S	O	N	D	Year
0000–0259	1	0	3	3	6	6	4	9	1	1	1	0	35
0300–0559	0	0	7	1	7	10	4	2	12	0	0	0	43
0600–0859	0	0	2	2	6	0	7	3	8	0	1	0	29
0900–1159	1	3	0	3	6	3	1	2	4	0	1	2	26
1200–1459	0	2	3	8	5	2	0	5	3	1	1	1	31
1500–1759	0	0	1	5	3	5	1	1	3	0	2	0	21
1800–2059	0	0	1	3	1	6	2	3	6	2	1	0	25
2100–2359	1	0	2	5	3	8	3	7	6	2	2	3	42
Total	3	5	19	30	37	40	22	32	43	6	9	6	252

ASSOCIATION WITH PREVAILING WIND DIRECTION AND DISCUSSION OF ANOMALOUS WIND EFFECTS

To obtain a true representation of the surface wind direction prevailing at the time of pressure jumps, and to remove any anomalous effects, the mean wind directions for the three-hour periods preceding and following the hour in which the pressure jump occurred were extracted. Figure 2(a) shows the number of observations of pressure jumps expressed as a percentage of the total number of pressure jumps for 30° ranges of wind direction.

The majority of pressure jumps occurred during periods of easterly winds; however, it must not be assumed that this direction is most frequent at Luqa, Malta. As shown by Figure 2(b), westerly to north-westerly winds are most in evidence and a secondary maximum in the frequency of pressure jumps occurs with winds in this sector. The distribution for individual months is similar. If the percentage frequency of pressure jumps in 30° ranges (see Figure 2(a)) is expressed as a percentage of the percentage frequency of winds occurring in the appropriate sector, a normalized distribution of pressure jumps associated with various wind directions is obtained. Figure 2(c) shows that the secondary maximum for north-westerly winds is absorbed in this distribution and that pressure jumps occur with predominantly easterly winds.

A pressure jump is defined by the Meteorological Glossary (London, Meteorological Office, 1972) as a rise of pressure often accompanied by the arrival of a line-squall. The wind criteria for a squall, however, were only satisfied on 10 occasions out of 252, but on many occasions near-squall conditions prevailed, sudden gusts or lulls often occurring with winds coming from a reciprocal direction, so that conditions could be described as 'effective squall' on a considerable number of occasions; the change of direction to a westerly rather than an easterly direction was attributed to a break-through of the wind regime at medium levels. Study of the 20 examples of pressure jumps of 4 mb or more to be discussed later showed that the wind normally veered with height from an easterly flow at the surface to a westerly flow at 700 mb.

Although rapid and marked changes in wind direction and speed frequently occurred at the time of a pressure jump, in the majority of cases the mean wind direction, that is to say over ± 3 hours, showed little change other than a slight backing as illustrated in Figure 2(c). The speed of the wind did not appear to be critical, with the mean wind speed for the three-hour period preceding the pressure jump varying from less than five knots to near-gale force, while the mean wind speed showed little change in the majority of cases afterwards.

Weather and cloud associated with pressure jumps

Usually the pressure jump occurs in cloudy conditions with unstable medium cloud or cumulonimbus present in the vicinity, while precipitation may vary from a trace to heavy rain associated with a thunderstorm; a squall may occur. On the other hand pressure jumps have occurred with clear skies or with no precipitation when cloud was present, and with little or no change of surface wind. Table IV shows the distribution of cloud and precipitation on occasions of pressure jumps during the five-year period studied. Since conditions vary considerably for individual pressure jumps it is of interest to look at the rather unusual weather associated with the examples shown on the barograms depicted in Figure 1.

Fine weather with light winds and little or no cloud continued from 24 to 27 July 1972, with the barogram showing the normal diurnal oscillations for a Mediterranean latitude. On 28, 29 and 30 July the normal diurnal pattern was interrupted at times and the trace became unsteady with several short-period fluctuations while periods of easterly winds occurred. These winds became fully established during the latter part of 30 July as a thundery depression moved north-eastwards across Tunisia into the Gulf of Gabes. An

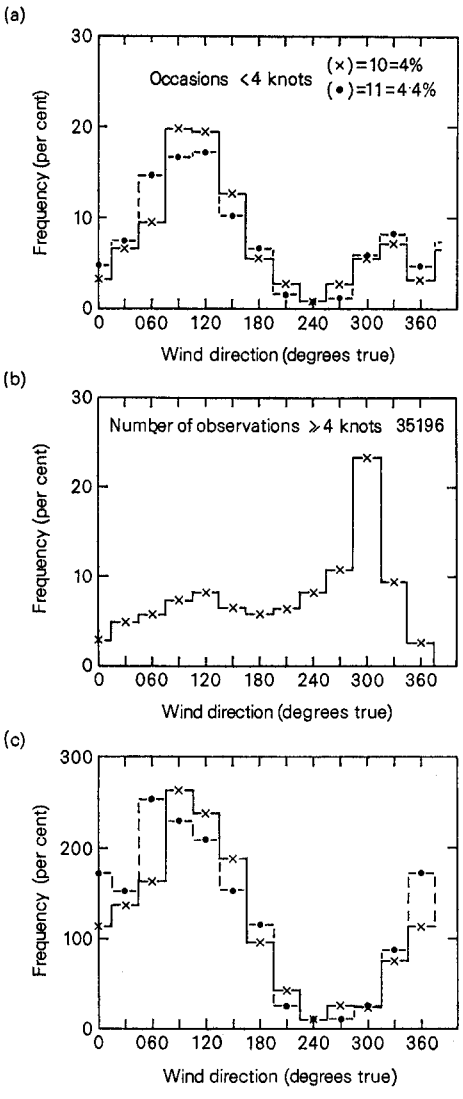


FIGURE 2—SURFACE WIND DIRECTIONS ASSOCIATED WITH PRESSURE JUMPS AND PERCENTAGE FREQUENCY OF WIND DIRECTIONS FOR LUQA, 1968–72

(a) Frequency of pressure jumps (as a percentage of total (252)) plotted against associated wind direction in ranges of 30°.
(b) Percentage frequency of wind direction in 30° ranges for wind speeds ⩾ 4 knots (all available hours 1968–72).
(c) Frequency of pressure jumps as percentage of frequency of associated wind direction plotted against direction in ranges of 30°.
–×– mean wind direction for three hours preceding a pressure jump
–·– mean wind direction for three hours following a pressure jump

associated trough of low pressure extended northwards to Italy and this moved eastwards across the Maltese islands on the evening of 31 July.

Unstable medium cloud increased to 7 oktas between 0300 and 0400 GMT on 31 July, giving intermittent rain for several hours, and the barograph oscillated markedly, with the pressure rising by over 5 mb in a few minutes at about 0730 GMT. Soon afterwards a roll cloud was observed below the main cloud layer and considerable locally raised dust reduced the visibility to about 3 km on the airfield. A report of property damaged by a whirlwind was received later in the day.

The wind (see Figure 3), which had been mainly south-easterly initially, increased rapidly at times to 25 kn with gusts to 31 kn during the period from 0500 to 0730 GMT, and veered to westerly at 0740 GMT. Immediately afterwards the wind returned to the south-east, with a gust to 41 kn during the shift, and within 10 minutes had decreased to about 10 kn. Further marked variations in the wind direction followed, with the speed varying between calm and 20 kn before the wind settled in the easterly sector again and the upper cloud started to disperse. This direction persisted until 2000 GMT when a north-westerly wind developed and the normal diurnal pressure pattern was re-established.

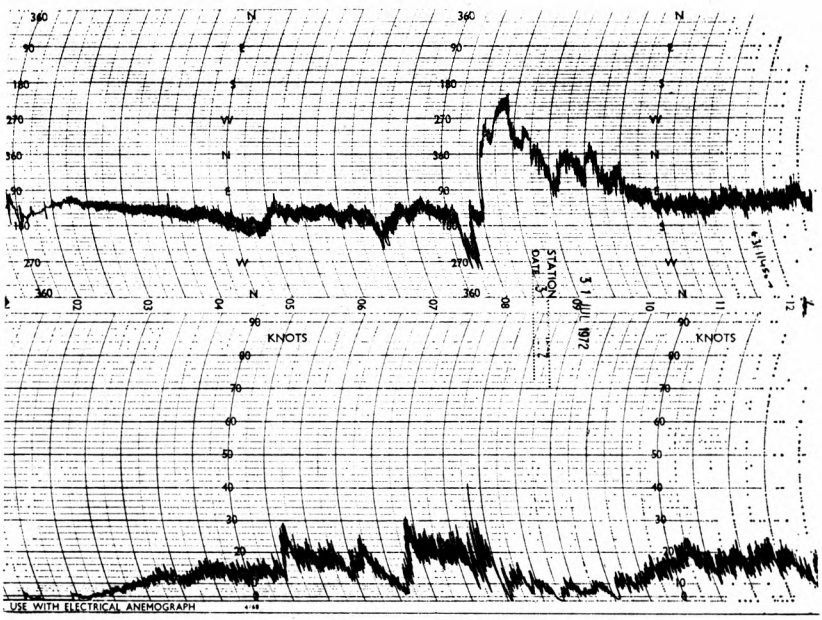


FIGURE 3—ANEMOGRAPH RECORD FOR LUQA, MALTA ON 31 JULY 1972

On 1 August the wind was light and variable, but the south-easterly set in on 2 August and was associated with an unsteady barograph trace; this situation was to last until a veer to the north-west on 3 August at about 1400 GMT when once again the normal diurnal pressure oscillation was resumed.

Of the three large pressure jumps which occurred during the period of south-easterly winds on 2 and 3 August, the first was not associated with any marked change in wind. The second, which occurred some six hours later with light south-easterly winds, was associated with a north-westerly squall of 36 kn followed by light and variable winds and subsequently a return to a light south-easterly wind.

The last pressure jump at 1245 GMT on 3 August coincided with the passage of a surface trough, and winds, which had initially been southerly to south-easterly 10–15 kn, increased rapidly to 25 kn with the pressure jump; thereafter they veered west to north-west, where they persisted for the rest of the day at about 15 kn. The significant feature of this last pressure jump was a marked roll type of cloud and two aircraft reports of turbulence. In the first a British Airways (European Division) Trident reported severe clear-air turbulence between 2000 ft and 3000 ft (approximately 0·6 km and 0·9 km). The other aircraft, an Antonov 24, also reported severe turbulence on the approach to Luqa, Malta, and was forced to make a second approach.

TABLE IV—CLOUD AND PRECIPITATION ASSOCIATED WITH PRESSURE JUMPS, 1968–72

Number of pressure jumps for the five-year period	252
Occasions with total cloud amount $\geq$ 5 oktas	233
Occasions with total cloud amount $<$ 5 oktas	19
Precipitation in hour in which pressure jump was observed	113
Precipitation in hour in which pressure jump was observed and also in preceding or following three hours	183
Thunderstorms or lightning seen in hour in which pressure jump was observed and preceding or following three hours	63
No precipitation in hour in which pressure jump was observed or preceding or following three hours	69
Squall occurring in hour in which pressure jump was observed	10

Twenty cases of pressure jumps of 4 mb or more

Table V lists the 20 occasions when pressure jumps of 4 mb or more occurred and these appear on the barograms depicted in Figure 4. The identifying numbers 1 to 20 given in the table are used for reference in the text and on the diagrammatic representations of the barograms. The times of the pressure jumps have been deduced from the daily register of meteorological observations, the clock errors of the barograms not being known with certainty.

On all the barograms except one, number 3 and 4, the large pressure jumps occurred during periods when the normal diurnal variation of pressure was disturbed, the trace was irregular, and often other significant pressure jumps followed in sequence. On 4–5 November 1968, however, the pressure jumps occurred during a thunderstorm associated with the passage of a marked upper trough after a period when the barometer had been normal in character, showing a minimum at 1500 GMT and a maximum at 2100 GMT. The rest of the jumps were not of this nature and occurred with surface winds having an easterly component.

Examination of the radiosonde ascent for Qrendi, Malta, showed that whereas the atmosphere on 4–5 November 1968 was unstable from near the surface to over 300 mb, the appropriate ascents for the other pressure jumps showed a marked similarity of type, having a potentially unstable layer between 800

TABLE V—PRESSURE JUMPS OF 4 mb OR MORE OBSERVED DURING THE FIVE-YEAR PERIOD 1968–72

Number	Time GMT	Date	Mean surface wind in degrees true and knots before (3 hours)	during hour	after (3 hours)	Remarks (times in GMT)
1	2149	11/6/68	080/09	040/08	010/14*	2230 effective squall
2	2248	11/6/68	060/08	310/20	050/09	250/20 gust 33 after lull
3	2247	4/11/68	220/13	220/21	300/15	0030 veer from SW to NW
4	0031	5/11/68	220/16	310/21	290/11	mean speed 26 kn gusts 38
5	1608	5/5/69	130/24	150/20	170/15	No significant change in wind
6	1651	5/5/69	130/24	150/20	170/15	1650 110/25 gust 34
7	1815	5/5/69	140/20	190/16	170/07	1805 effective squall 230/24 gust 32
8	1100	24/6/69	140/13	110/17	110/16	1110 gust 24 kn, 1215 gust 29 kn
9	2059	3/7/69	110/10	110/10	020/03*	2100–2145 300/05 gust 16
10	2245	24/8/69	190/10	200/13	150/14	2230 160/15 gust 19
11	0330	14/3/71	110/19	120/16	120/24	0330 sudden lull 200/05 or less
12	0415	14/3/71	120/18	120/22	130/25	No significant change in wind
13	0945	9/5/71	090/15	110/18	090/14	0945 no significant change in wind, 1015 calm
14	1145	9/5/71	100/13	080/14	100/18	1030–1200 slow increase to 100/20 gust 29
15	0215	6/7/71	120/13	310/06	050/07	0210 calm, followed by sharp increase to 300/12 gust 16
16	0726	6/7/71	080/10	120/16	130/15	0710 230/10
17	0730	31/7/72	160/16	150/20	130/11*	0735 effective squall 160/22 gust 29
18	2245	1/9/72	100/11	110/08	110/13	2215 variable, less than 5 kn
19	0335	6/9/72	110/09	110/13	050/11	0350 effective squall 310/19 gust 24
20	0515	15/9/72	130/12	250/12	090/11	0520 variable 5 kn 0525–0600 250/12 gust 18

Notes: Mean wind speeds and directions calculated independently as scalar quantities.
* Occasions when the wind direction fluctuated through more than 90°.

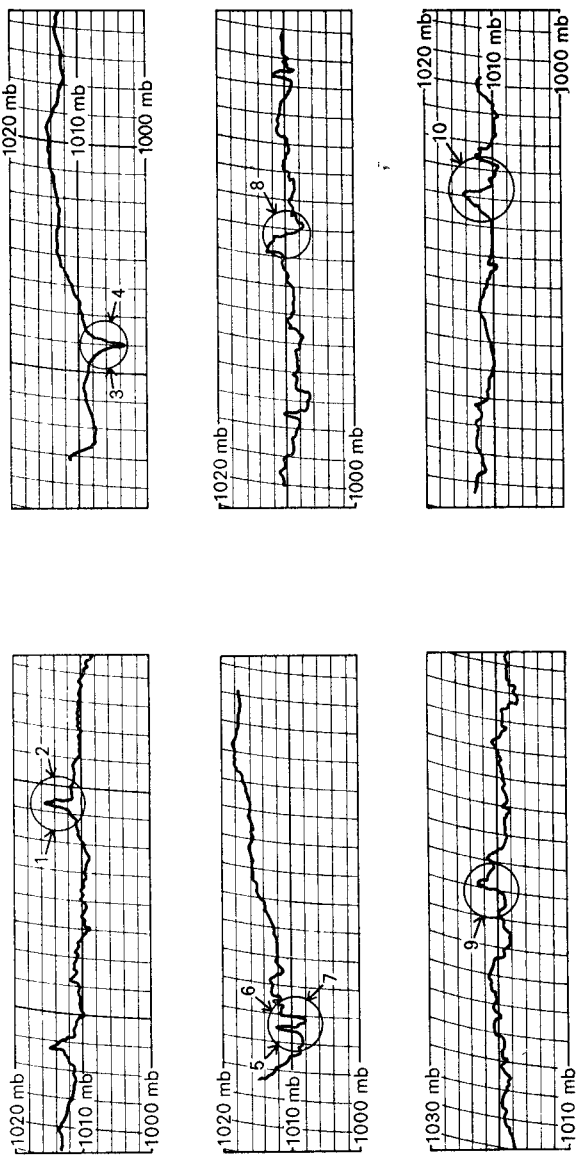


FIGURE 4—DIAGRAMMATIC REPRESENTATION OF EXAMPLES OF BAROGRAMS ON WHICH PRESSURE JUMPS OF 4 mb (OR MORE) WERE RECORDED

The barograms shown are for the following dates, with the number identifying the particular pressure jump, as listed in Table V, in brackets. 11 June 1968 (1 and 2); 4/5 November 1968 (3 and 4); 5 May 1969 (5, 6 and 7); 24 June 1969 (8); 3 July 1969 (9); 24 August 1969 (10). Horizontal lines are at intervals of 2 mb; curved lines are at intervals of 3 hours.

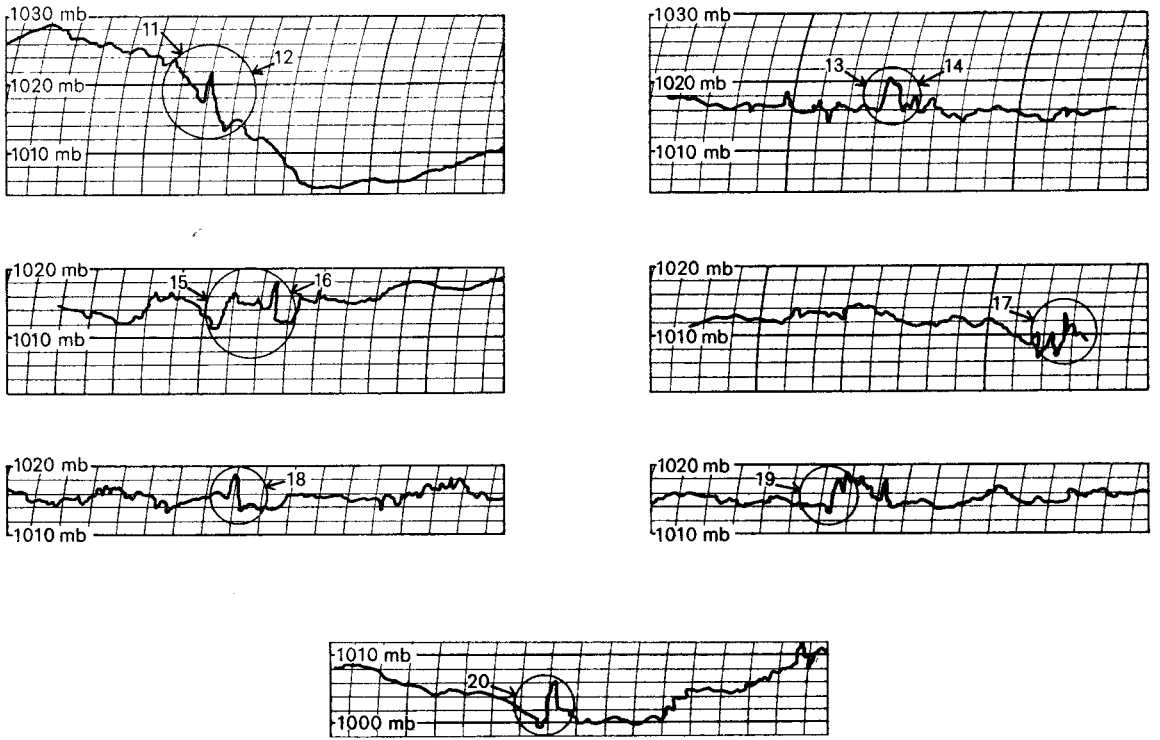


FIGURE 4—*continued*

The barograms shown are for the following dates, with the number identifying the particular pressure jump, as listed in Table V, in brackets. 14 March 1971 (11 and 12); 9 May 1971 (13 and 14); 6 July 1971 (15 and 16); 31 July 1972 (17); 1 September 1972 (18); 6 September 1972 (19); 15 September 1972 (20).

and 500 mb, approaching the dry adiabatic lapse rate (on some ascents this layer was dry, and on others considerable moisture was present) above an inversion at heights between 950 and 850 mb, and a cool layer near the surface. A typical ascent is shown in Figure 5. Examples of large and rapid changes of pressure in thunderstorms, often associated with upper troughs and/or squalls, of the type observed on 4–5 November 1968 are well documented. Excluding this event there remains the large proportion of pressure jumps recorded at Luqa which fall into a class of their own and occur in rather special conditions.

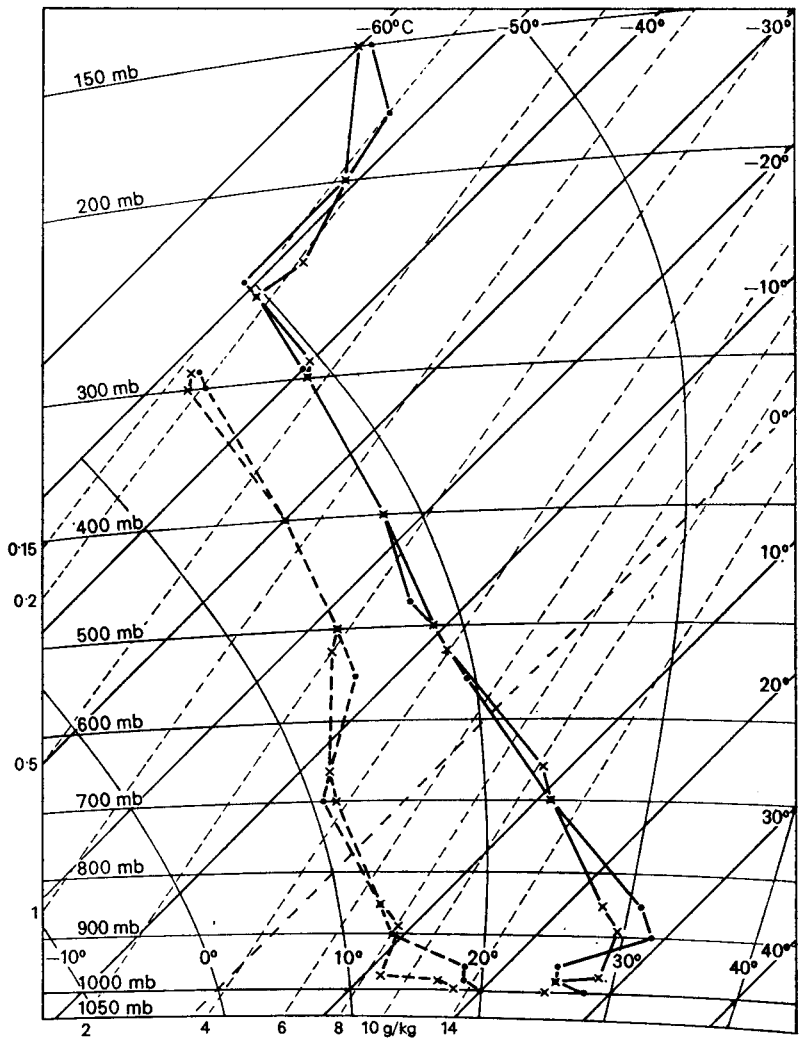


FIGURE 5—RADIOSONDE ASCENTS FOR QRENDI, MALTA, ON 31 JULY 1972

× —— × 00 GMT dry-bulb temperature
× – – × 00 GMT dew-point temperature
· —— · 12 GMT dry-bulb temperature
· – – · 12 GMT dew-point temperature

Of the 18 pressure jumps remaining all were found to be cloudy except one, 3 July 1969 (9), and precipitation fell on 11 occasions. Cloud and precipitation did occur within three hours of the jump on 3 July 1969, and, in all, 8 out of the 18 occasions had evidence of thunder within ± 3 hours. Perhaps the most important point about these observations is that although anomalous winds were recorded on several occasions (1 and 2, 7, 9, 11, 14, 15, 16, 17, 19 and 20) which approached squall criteria, there were other occasions (5, 6, 8, 10, 12 and 18) when no marked changes in wind occurred near the time of the pressure jump despite fluctuations of 4 mb or more. Comparison of the mean wind directions for three hours preceding and following the pressure jump confirmed the tendency for backing previously shown in Figure 2(c).

The winds, which had an easterly component at the surface, veered with height to become mainly westerly by 700 mb, this direction being backed some 30 to 40 degrees from the norm, as were the wind directions above 700 mb. The wind speed varied considerably from one jump to the next and there was no evidence of a critical wind speed at any particular height. Figure 6 shows the upper-wind distribution for the occasions of large pressure jumps; it is based on the mean surface wind in the three-hour period prior to the jump and the appropriate radar winds for Qrendi, Malta.

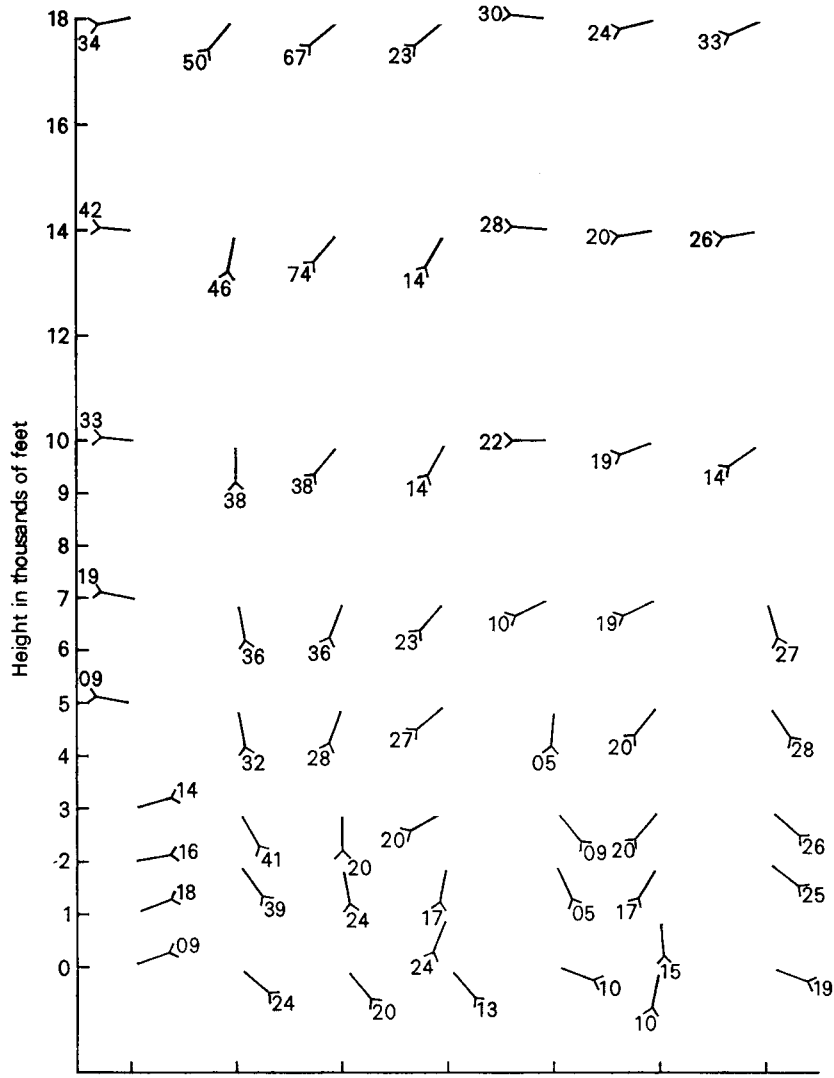
The vector mean winds were computed for these occasions and plotted as a hodograph, Figure 7, showing the mean wind shear typical of large pressure jumps. This shear pattern was found to be present on most occasions when pressure jumps occurred at Malta, and may therefore be used as a guide to indicate the likelihood of pressure jumps, and may also be usefully employed to explain anomalous surface-wind effects. It should be noted nevertheless that the hodograph shear pattern in itself is not sufficient to induce pressure jumps; nor should the latter if they occur be interpreted as indicative of anomalous winds at the surface, since there were several observations of pressure jumps in excess of 4 mb when the surface wind showed little or no significant change.

The highest gust recorded for this set of observations was 41 kn and this figure is in accord with the value found by using the regression equation of Fawbush and Miller (1954) which is strictly applicable to gusts in thunderstorms.

The cases discussed here were studied to see if any oscillatory motion was present for pressure, wind and temperature. Although on occasions pairs of jumps appeared to be similar in characteristic (see jump preceding number 17), the overall impression was that the pressure jumps were random in nature. Similarly, although on two occasions marked temperature changes were recorded, there being a rise of 9 deg in one hour and then a rapid fall of 6 deg on 24 June 1969 (8) and on 31 July 1972 (17) a rise of 2·5 deg followed by a fall of 1·5 deg during the effective squall, on all other occasions there were no significant changes nor were there any temperature oscillations. Slight wind oscillations occurred after pressure jumps 7, 9 and 18.

Turbulence

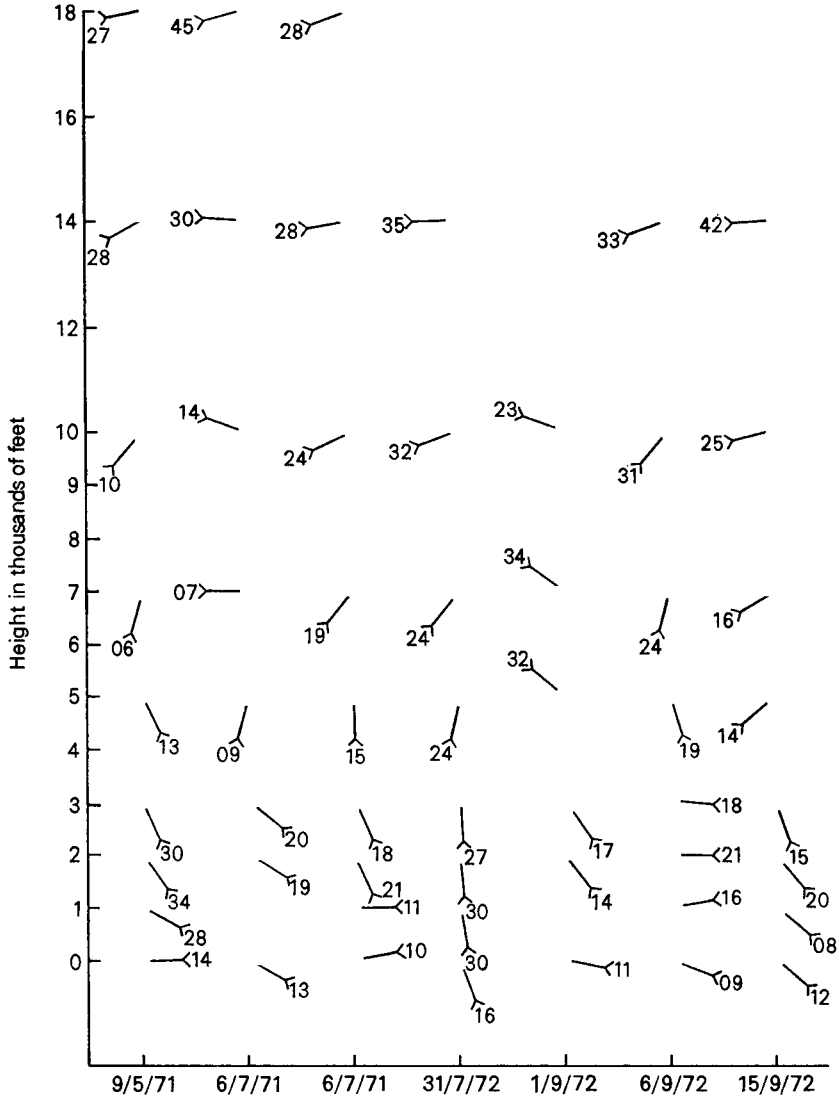
The sequence of events leading to the reports of severe low-level turbulence on 3 August 1972 have been discussed earlier. No other reports of turbulence which could have been associated with a pressure jump were received, possibly owing to the small chance of an aircraft movement coinciding with a pressure jump or to the fact that near-surface mechanical turbulence is frequently found



Date	11/6/68	5/5/69	5/5/69	24/6/69	3/7/69	24/8/69	14/3/71
Pressure-jump No. and time (GMT)	1–2149 2–2248	5–1608 6–1651	7–1815	8–1100	9–2059	10–2245	11–0330 12–0415
Time of upper winds (GMT)	1800	1200	1800	0600	1800	1800	0000

FIGURE 6—UPPER WIND DISTRIBUTION ASSOCIATED WITH PRESSURE JUMPS OF 4 mb OR MORE

Wind directions are in degrees true and wind speeds are expressed in knots (1 kn ≈ 0·5 m/s).



Date	9/5/71	6/7/71	6/7/71	31/7/72	1/9/72	6/9/72	15/9/72
Pressure-jump No. and time (GMT)	13—0945 14—1145	15—0215	16—0726	17—0730	18—2245	19—0335	20—0515
Time of upper winds (GMT)	0600	0000	0600	0600	1200 (1800 NIL)	0600 (0000 NIL)	0000

FIGURE 6—*continued*

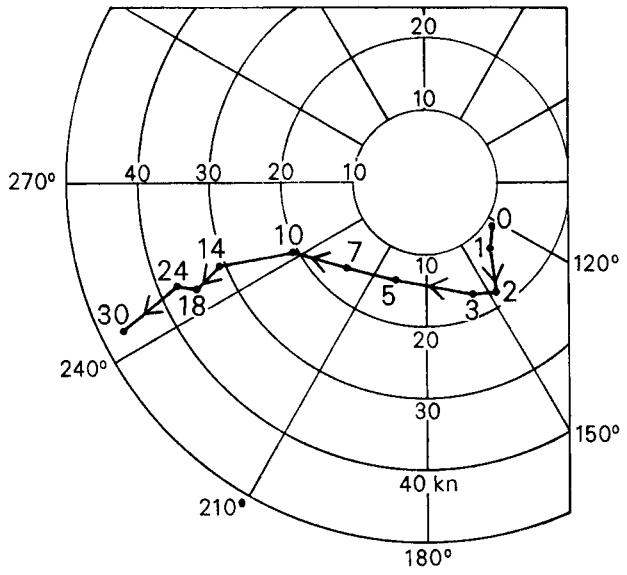


FIGURE 7—HODOGRAPH OF VECTOR MEAN WINDS ON OCCASIONS OF LARGE PRESSURE JUMPS

Heights are indicated in thousands of feet (1000 ft = 304·8 m).
The diagram is based on 14 observations.

with winds from a westerly direction at Luqa, Malta because of the proximity to the runway of a large hangar, and anything less than severe turbulence would probably not result in an aircraft report.

A certain similarity was noted between conditions obtaining during occasions of severe low-level turbulence reported by Hardy (1971) for the eastern Mediterranean and those which were found when pressure jumps occurred at Malta. In particular the following factors were remarkably similar.

1. Synoptic types common to the central and eastern Mediterranean.
2. Winds veering from a direction with an easterly component at the surface to a westerly above 700 mb.
3. Unsteady barograph trace (pressure jumps were also reported by Hardy).
4. On most occasions large amounts of medium or high cloud were observed.
5. Potentially unstable medium layers approaching the dry adiabatic lapse rate overlay a cool surface layer with an inversion at about 900 mb.

While it would appear that the conditions associated with pressure jumps at Luqa, Malta, are potentially likely to give clear-air turbulence, certain dissimilarities to those given by Hardy should be noted. They are:

1. Pressure jumps could occur at any time of the year—the turbulence reports of Hardy were restricted to the period from February to April.

2. A frontal system said to be usually associated with a surface low and strong upper jet was not necessary to produce conditions favourable to pressure jumps at Luqa, Malta, although a certain similarity of synoptic type is necessary to satisfy the conditions given above.

3. The minimum temperature recorded on the preceding night was not always above average—no significant correlation with the preceding night's minimum temperature having been found for the Luqa, Malta data.

Discussion

It has been demonstrated that pressure jumps at Luqa, Malta can occur at any time of day or year and with varying wind speeds and directions; however, they occur most frequently in rather special conditions. These require the wind to veer from an easterly component at the surface to a westerly by about 700 mb, while a potentially unstable medium layer (usually of desert origin) overlies air cooled by the sea track, resulting in a two-layer structure with an inversion at about 900 mb. The following synoptic types are therefore most likely to produce pressure jumps and the associated wind features:

A. Stationary or slow-moving upper trough–ridge patterns over the central Mediterranean, resulting in low pressure over Tunisia and a ridge of high pressure to the east of Malta.

B. Transient southerly or south-easterly airstreams ahead of desert lows or troughs moving north-eastwards from the west coast of Libya or south-eastwards from the north coast of Tunisia.

Given the conditions in which pressure jumps have been found to be most frequent we have an analogy with the work of Townsend (1964) who showed experimentally in the laboratory that convection in an unstable layer may produce internal waves within the interface between two fluids. He proceeded to suggest then that the energy of these waves would be dissipated in shallow patches of turbulence within the interface. A report of turbulence of this nature has previously been made by the present author (Perry, 1972). A similar conclusion was reached by Pothecary (1954) who showed anomalous fluctuations of wind to occur over a large area as wave oscillations induced by convectional downdraughts associated with an area of thunderstorms propagated away from the initial outflow of cold air.

In this investigation there is substantial evidence that most of the pressure jumps occurred at a time when the middle layers were overturning, causing an irregular barograph trace, and that the pressure jumps resulted from the large vertical accelerations in marked updraughts and downdraughts. Evidence was visible in the frequency of castellanus clouds and mamma observed at these times, and in the sudden onset of rain, albeit on some occasions only a few large drops, which accompanied most pressure jumps.

It may be postulated that when conditions are favourable for pressure jumps, the overturning motion will produce waves within the inversion at a lesser height which may degenerate into turbulence patches. Furthermore, given sufficient impetus, the wind regime above the inversion breaks through to the surface, producing a squall and a wind direction approaching that which prevails at about the 850-mb level. The change of mean wind direction measured

over three hours, preceding and following a pressure jump, showed a tendency for backing, and although surface temperatures did not show evidence of a fall of temperature, this backing of wind may be indicative of cooling in the inversion layer.

It also follows that in favourable conditions of lapse rate and wind shear, which are beyond the scope of this investigation, induced waves in the inversion will on occasions produce the oscillations in wind speed and direction noted on a few occasions here and previously reported by Kirk (1961 and 1963a–d) and Lamb (1954).

Finally, it is logical to assume that the conditions for pressure jumps at Luqa, Malta are not unique and that in similar synoptic types they might occur over large areas of the Mediterranean, while the intensity of the phenomena associated with the rapid changes of pressure would be enhanced if they occurred as a prelude to the passage of a surface or upper-air trough or frontal system.

Forecasting pressure jumps, anomalous surface winds and severe low-level turbulence

The analysis of pressure jumps has shown that for Luqa, Malta, the large majority occur as a result of special meteorological conditions. These are summarized in an Appendix which may be used as a forecasting guide to occasions when pressure jumps, anomalous surface winds and severe low-level turbulence might be expected to occur.

Earlier, in the discussion of the weather and cloud associated with pressure jumps, it was shown that although the barograph trace was irregular for long periods and conditions were favourable to pressure jumps, only a few significant jumps actually occurred. In investigating the conditions at the time of the jumps in excess of 4 mb it was also found that not all these pressure jumps were associated with anomalous surface winds; indeed, on several occasions little or no significant change in the surface wind occurred. It follows that although the majority of the pressure jumps at Luqa, Malta occurred within the conditions given in the Appendix, the converse is not true, and the Appendix should therefore be treated as a guide to periods when pressure jumps, anomalous surface winds or low-level turbulence might occur, and as a test of anomalous observations which might otherwise be discarded as erroneous.

Users of this advice, more especially pilots of light aircraft and captains of marine craft, while usually aware of the danger associated with the thundery squalls produced by cumulonimbus clouds in the Mediterranean are often surprised by the rapid changes which sometimes occur, either with little or no cloud or with apparently innocuous patches of unstable medium cloud, and it is considered that the Appendix, sensibly used, would be of value in these circumstances. Additionally, the Appendix may be of considerable value in regard to the use of altimeter settings in defining occasions when sudden changes of pressure can occur which present a hazard to navigation.

Conclusions

Pressure jumps are likely at Luqa, Malta and indeed also over other Mediterranean localities when there is a two-layer airflow with a potentially unstable layer in the middle atmosphere overlying a near-surface layer which has been cooled by advection over the sea. In such conditions the barogram becomes

irregular and anomalous changes of wind may accompany sharp changes of pressure which can exceed 4 mb in less than an hour and may do so in a few minutes.

These conditions are also conducive to the production of severe low-level turbulence and as such should be watched for the development of rotors or line-squalls. On many occasions they explain the oscillatory variations in wind, pressure and temperature and may account for the various reports of violent Mediterranean squalls which are difficult to explain within the context of the normal synoptic analysis. A forecast guide is given in the form of an Appendix which may be used to predict periods when such conditions might occur or to investigate their occurrence in retrospect.

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Appendix I—Forecasting guide

This section summarizes in convenient form the synoptic developments which may result in the occurrence of pressure jumps, anomalous surface winds and severe low-level turbulence at Luqa, Malta. Situations which, in the light of experience, are considered to be favourable, occur when:

(a) stationary or slow-moving upper trough/ridge patterns over the central Mediterranean produce an area of low pressure over Tunisia and a ridge of high pressure to the east of Malta, or

(b) transient southerly or south-easterly airstreams develop ahead of desert lows or troughs moving either north-east from the west coast of Libya or south-east from the north coast of Tunisia, and

(c) as is often the case in these circumstances the surface winds over Malta become easterly and veer with height to become westerly by 700 mb (see

example in Figure 7), while the radiosonde ascent shows a potentially unstable layer in the middle troposphere separated from a cooler surface layer by an inversion or stable layer at about 900 mb (see example in Figure 5).

If either (a) or (b) results in (c) then

(1) the barogram changes in character and becomes irregular (see example in Figure 1) and severe low-level turbulence may occur within the inversion between the two air flows, i.e. between the cooler surface layer and the potentially unstable layer above.

(2.1) If unstable medium cloud is present (i.e. mamma or castellanus) a pressure jump is probable, often with onset of rain; otherwise

(2.2) if the ascent is dry (i.e. only a trace of Ac) then a pressure jump is still possible but less likely;

(3) after the first pressure jump others may follow, either positive or negative, and may on rare occasions exceed 4 mb (see example in Figure 4);

(4) anomalous surface winds may occur which could satisfy squall criteria, or because of the rapid change in direction (possibly 180°) may be in effect equivalent to a squall (see example in Figure 3); and

(5) a squall line or rotor cloud can occur especially if an upper trough or surface discontinuity is approaching, and may be associated with severe low-level turbulence.

551.525.2

EXTREME VALUES OF GRASS-MINIMUM DEPRESSIONS AT WEST RAYNHAM

By M. N. PICKUP
(Meteorological Office, West Raynham*)

SUMMARY

Grass-minimum temperatures were examined to establish the annual frequency and seasonal variations of extreme values of their depression below screen minima.

1. INTRODUCTION

Davies (1975) has recently suggested that grass-minimum depressions are greater in south-west England than in eastern England, and also that nights with large grass-minimum depressions may be most frequent in spring.

A check of the depressions at West Raynham, using the data extracted for an earlier paper by Pickup (1976) revealed that there is little difference between the two locations as regards the magnitude of the largest depressions, and that the frequency of such depressions during the year shows a more random variation at West Raynham than at Westbury-on-Trym.

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* The author is now at Manchester Weather Centre.

2. Data

The West Raynham observations for the period from 1 January 1961 to 19 March 1970 had previously been analysed—a total of 3240 nights. The nights since the reopening of the office in 1972 were added to include the period from 26 January 1972 to 31 March 1975—809 nights, making a grand total of 4049 nights.

From August 1969 to March 1970, and again from January 1972 to March 1975 there were no weekend observations.

In order to obtain a direct comparison with the figures for Westbury-on-Trym a separate analysis for the period from 26 January 1972 to 31 December 1973 was also completed.

3. Results

The results of the analysis for the period from January 1972 to December 1973, which includes mean values of the depression Δ of the grass-minimum temperature below the screen-minimum temperature, and the percentage frequency for each month of observations for which this depression reached or exceeded 6·5 deg are shown in Table I.

The number of nights with $\Delta \geqslant 6{\cdot}5$ deg, and the maximum value of Δ for each month, for the period from January 1961 to March 1975, are shown in Table II.

4. Discussion

A direct comparison between the West Raynham and the Westbury-on-Trym results for 1972–73 shows little similarity. The mean values of Δ for each month at West Raynham were almost half those at Westbury-on-Trym.

The maximum monthly values of Δ are in closer accord but would seem to tend to support Davies's view that grass-minimum depressions in south-western England are greater than those found in eastern England. The maximum depression at West Raynham was greater than that at Westbury-on-Trym in only two months—May and September.

As these large values of Δ are infrequent at West Raynham—1 night in 108 for the period from January 1961 to March 1970; 1 night in 37 for the period from January 1972 to March 1975; 1 night in 78 overall—it would seem logical to consider as long a period as practicable in order to get a true picture of the annual and monthly frequency.

The results in Table II show that in all months during the period from January 1961 to March 1975 there was at least one night with a depression of 6·6 deg, and seven of the months had depressions greater than those recorded at Westbury-on-Trym during the period from January 1972 to December 1973. Of the 52 occasions at West Raynham, 30 occurred in the period from January 1961 to March 1970 and 22 between January 1972 and March 1975. The years with the greatest and least number of occasions of $\Delta \geqslant 6{\cdot}5$ deg were 1973 with 9, and 1965 and 1968 with only 1 each.

Davies has suggested that there might be a maximum frequency in spring. The West Raynham results show a far more variable spread throughout the year, with maxima in February, May and September with 8 each, and minima in January and November with 1 each. It is interesting to note that all the

TABLE I—GRASS-MINIMUM DEPRESSION (Δ) AT WEST RAYNHAM FOR THE PERIOD FROM JANUARY 1972 TO DECEMBER 1973

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Mean (deg)	1·66	1·98	2·89	2·71	2·73	2·63	2·10	2·53	2·70	2·33	2·15	1·79	2·38*
Highest (deg)	5·4	8·0	6·1	7·1	8·2	6·9	6·5	6·2	7·7	6·7	6·6	5·4	8·2†
No. of obs.	26	41	49	36	43	43	45	41	46	46	46	35	497‡
No. of obs. ⩾ 6·5 deg	0	3	0	1	2	1	1	0	2	1	1	0	12‡
Percentage of obs. ⩾ 6·5 deg	0	7	0	3	5	2	2	0	4	2	2	0	2*

* Mean † Extreme ‡ Total

TABLE II—GRASS-MINIMUM DEPRESSION (Δ) AT WEST RAYNHAM FOR THE PERIOD FROM JANUARY 1961 TO MARCH 1975

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
No. of obs. ⩾ 6·5 deg	1	8	4	2	8	6	5	3	8	3	1	3	52‡
Highest (deg)	6·8	8·9	7·6	7·1	8·2	8·0	7·0	7·1	7·7	7·4	6·6	8·6	8·9†

† Extreme ‡ Total

8 occasions in February have occurred since the office reopened in 1972, which supports the suggestion that it is desirable to consider long periods when investigating variation in the incidence of large values of Δ.

The grass-minimum temperatures at Westbury-on-Trym are read every 24 hours and refer to the preceding 24, whereas the West Raynham minimum values refer to the period from 21 GMT to 09 GMT. Although the different periods and sites may account for part of the difference between the two areas, there is still a large variation in the percentage frequency of nights with $\Delta > 6{\cdot}5$ deg, namely 11 per cent at Westbury-on-Trym and only 1 or 2 per cent at West Raynham. It will be interesting to see the change in frequency at Westbury-on-Trym if longer periods can be investigated.

It has already been suggested by Pickup (1976) that maximum values of Δ occur when the air is dry initially and when, subsequently, little dew or frost forms. During this investigation it was noted that many of the occasions with $\Delta \geqslant 6{\cdot}5$ deg occurred during, or following, a dry spell.

5. Conclusion

Suitable conditions such as clear skies and light winds being given, values of the grass-minimum depression greater than 6·5 deg are likely at West Raynham at any time of year; this result had previously been discovered for Westbury on-Trym, and is now presumed to hold in other areas as well.

The possibility of large grass-minimum depressions may increase during spells of dry weather. An investigation to find a possible correlation between rainfall anomaly and Δ is now being undertaken.

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551.593.653

NOCTILUCENT CLOUDS OVER WESTERN EUROPE AND THE ATLANTIC DURING 1975

By D. H. McINTOSH and MARY HALLISSEY
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Table I summarizes the observations of noctilucent cloud made over western Europe and the Atlantic during 1975. These reports were provided by the network of observers, professional and amateur, associated with the Aurora Survey centred at the Balfour Stewart Auroral Laboratory of the University of Edinburgh.

The dates in Table I cover the period of optimum viewing of the clouds between geographic latitudes 50° and 60°N. The periods of time during which the clouds were observed appear in the second column. These should not be taken as being necessarily the total duration of the display; this is stated where possible, but it is obviously difficult, particularly for voluntary observers, to record a display to the point of disappearance. Brief notes on the displays appear in the third column. In the remaining columns, details of the relevant station co-ordinates are listed to the nearest half degree, and the maximum elevation and limiting azimuths of the observed cloud, where known.

TABLE I—DISPLAYS OF NOCTILUCENT CLOUDS OVER WESTERN EUROPE AND THE ATLANTIC DURING 1975

Date—night of	Times UT	Notes	Station* position	Time UT	Max. elev.	Limiting azimuths *degrees*
6/7 May	2200	Small patch of NLC, 30° elevation in NW.	57°N 02°W	2200	30	345
20/21	2050	Patch of bright NLC, possibly whirls, high to NW against veil background.	51°N 01°E	2050	30	345
30/31	2320–2400	Faint NLC seen above clearly visible north horizon. Observations discontinued 2400.	56°N 04·5°W	2320	4	340–355
7/8 June	2130–0045	NLC—no details.	55°N 04·5°W			
	0400	NLC disappearing to NE.	52·5°N 07·5°W	2345	6	
				0045	3	
9/10	2225–0020	Weak display seen in otherwise clear sky; banded structure drifted slowly west and south.	56°N 04·5°W	2335	40	295
				0010	20	350
			55°N 04·5°W			
10/11	2132	Veil and banded patch of NLC visible in otherwise clear sky.	51°N 01°E	2132	15	335
12/13	2305–0215+	From Milngavie (56°N) NLC became visible at 2302 in NW.	56°N 04·5°W	2330	13	290–010
				0035	10	
		Between 2400 and 0030 there was	55°N 04·5°W			
		some drift to west and the bands	54°N 09°W	2400	6	330–008
		had bright green iridescent sheen.	53·5°N 09°W	2338	7	310–025
		Display seen as bright from Ireland;		0130	11	345–015
		from Scotland though not bright		0215	14	325–005
		'rather exquisite in texture and colour'—brightest 0035 when numerous whirls appeared to north. Photographed Kiltimagh, western Ireland, 0200.	52°N 10·5°W			
14/15	2250–0137	Clear skies noted 2230 Dundee (56·5°N), medium bright NLC in broad bands visible at 2250 obscured by tropospheric cloud after 2330. At 0030 NLC was seen from Aberdeen as extensive display of diffuse structure over entire northern sky. Isolated patches and bands photographed Edinburgh 0119 and 0129.	57°N 02°W	0030	90	270–080
			56·5°N 03°W	2250	12	
			56°N 03°W			
15/16 June	0200–0210	Possible sighting of NLC high NW just before spread of dawn light.	52°N 02·5°W	0200	58	345
16/17	2210–0235	Small patches of NLC seen in north —at times between tropospheric clouds.	56·5°N 07°W	2400	27	340–045
				0100	25	045
			55°N 04·5°W	2300		355
			53°N 08°W	0145	10	350–040
				0220	15	
17/18	2140–2315	Possible NLC showing through gaps in tropospheric cloud.	55°N 04·5°W	2230		355
18/19	2117	Bright banded patches of NLC seen against veil background.	51°N 01°E	2117	5	330–025
19/20	0050–0125	Characteristic silvery streaks of the NLC showing brighter than high tropospheric clouds.	57·5°N 03·5°W	0100	21	040–060
20/21	2210	Possible NLC to north.	55°N 04·5°W			
21/22	0300	'Glow' reported from Ocean Weather Ship *Weather Reporter* thought to be NLC.	53°N 20°W			
25/26	2325–2400	Faint wisp of NLC suspected at 2325; very faint and with little structure at 2345. Photographed at 2332.	57°N 02°W	2400	8	020
26/27	0100–0200	Small patches of NLC low in NNE, moving slightly south and west before fading into light sky.	56·5°N 07°W	0100	3	020
				0200	9	360–045

* To nearest 0·5 degree.

TABLE I—*continued*

Date—night of	Times UT	Notes	Station position	Time UT	Max. elev.	Limiting azimuths *degrees*
27/28 June	2100–2200	Typical banded structure seen through binoculars. Westerly movement noticed 2115 with brightening in NW—this formation faded 2135 but new formations in NE to 12° elevation. These last observed very faint in NNE.	55°N 14·5°E	2100	20	345–045
				2115	25	
				2135	12	045–
				2150	12	360–045
28/29	2230–0235	This widely observed display reported from Denmark to be exceptionally brilliant (2230). At Lerwick three main bands lay N–S across zenith. Bands, billows and transverse ripples seen from northern stations to high elevation. Little movement seen from more southern stations.	60°N 01°W	0010	90+	
				0030	90	
			57·5°N 03·5°W	2345	23	330–050
				0040	20	340–010
			57°N 02°W	2340	20	
				2400	45	
			56°N 03°W			
			55·5°N 01·5°W	0050	10	360–045
			55°N 14·5°E	2230	12	340–020
				2345	20	340–020
			54·5°N 06°W	0100	50	340–075
			54°N 02·5°W	0105	15	
			54°N 04·5°W	2350	8	010–035
				0030	8	015–025
			54°N 09°W	0155	10	
			53·5°N 03°W	2345	4	355–020
				0100	4	360–045
				0130	4	360–010
			53°N 02·5°W			
2/3 July	0050–0130	Rather faint 'streak' of NLC 10° elevation and parallel to N horizon; small patch of billows in NNE.	60°N 01°W	0050	10	360–045
3/4	2250–0145	Faint NLC first seen in NE; elevation increasing until still visible NW–ESE through encroaching tropospheric cloud.	60°N 01°W	2250	20	050
				2315	30	050
				2350	50	080
				0050	65	120
				0135	10	330
4/5	2250–0250	First reported from Aberdeen (57°N) and by 2310 seen also to high elevation in southern Norway, Tiree and Skye. NLC built up to extensive display of parallel bands, close-packed herring-bone pattern wave structure, with typical drift movements to W and S. NLC seen from Lerwick covered much of sky. (Display photographed 0008–0128 in Edinburgh.)	60°N 01°W	2355	90+	
				0055	90+	
			59°N 09°E	2315	58	
			58°N 05·5°W	2400	80	
			57·5°N 03·5°W	2350	20	045
			57·5°N 06°W	2305	20	330–050
				2330	35	330–000
				0135	25	360–085
			57·5°N 07·5°W	2330	29	320–050
				2400	30	320–065
				0030	28	320–060
				0120	33	330–070
				0150	47	330–070
			57°N 02°W	2310	22	340–020
			56·5°N 03°W	0100	20	360
				0200	20	
			56·5°N 07°W	2330	18	340–035
				0245	15	050
			56°N 03°W	0050	20	
			55°N 04·5°W			
6/7	0005–0110	NLC in NNE partly obscured by tropospheric cloud. The lower edge of banded patches tinged with red on E.	57·5°N 03·5°W	0100	15	360–030
7/8	2310–0015	Moderate intensity NLC seen as sky darkened; bands with herring-bone structure and small diffuse patches.	58°N 06·5°W	2310	11	345–030
8/9	2330–0130	Faint NLC display seen in otherwise almost clear sky; bands, patches, wisps and wave structure identified.	58°N 06·5°W	2330	9	025–045
				0020	6	010–055
				0130	6	
			57·5°N 07·5°W	0025	5	040–045
13/14	0150	Weak NLC veil in NNW viewed during period clear of tropospheric clouds.	53°N 0·5°E	0150	8	340–360
14/15	2135	Complicated structure of bright NLC bands and billows against veil background.	51°N 01°E	2135	55	
17/18	2130–0150	Low-brightness banded areas of NLC seen in Denmark, which increased in brightness to beautiful blue/green display with usual westward movement. Seen in western Scotland as small patches of NLC NW–NNE and large patch to NE. Colour prints from Håstrup.	56·5°N 07°W	2350	9	315–020
				0050	10	045
			55·5°N 10·5°E	2130	10	340–020
				2240	12	
17/18	0325–0415	Pilot of eastward bound transatlantic aircraft reported flying under bright banded display of NLC.	55°N 40°W	0325		045–090
			55°N 30°W	0407	60	360–090
			56°N 28°W	0415	90+	

TABLE I—*continued*

Date—night of	Times UT	Notes	Station position	Time UT	Max. elev. degrees	Limiting azimuths
18/19 July	2350	NLC visible NNW–N'E through gaps in tropospheric cloud.	56·5°N 07°W	2350	12	345–010
20/21	0050–0250	Patches of NLC of varying brightness NW and NE–ENE. Banded structure discernible from Kirkwall. Single streak still visible in NW from Aberdeen at 0240.	59°N 03°W	0100	10	030–050
				0200	15	030–050
			57·5°N 03·5°W	0050	8	045–080
				0150	10	045
			57°N 02°W	0200	25	345–360 and 050–070
			56·5°N 03°W	0145	7	027–034
21/22	2105–2215	Faint NLC bands seen from Alrø above heavy tropospheric clouds in NNW, developing to brighter and extensive formations (mainly bands) WNW–NE. Covered by cumulus clouds at 2215. (Photographed 2137–2205.)	56°N 10°E	2105	15	345
				2137	18	290–045
25/26	2035–2100	Banded formation seen from	57°N 9·5°E	2250	7	320–360
	2210–2315	Denmark to form in NNW, fading 2100. Seen again faintly 2210; increased activity and bright formation 2300.	56°N 10°E	2035	8	345–360
				2045	10	
				2210	12	
30/31	0100–0300	Horizontal bands and patches seen low NE from Aberdeen and Kirkwall. Long-focus photographs were taken in Aberdeen when cloud was low but structurally clear in NE, 0154–0227.	59°N 03°W	0100	5	010–060
			57°N 02°W			045
31 July/1 Aug.	2055–2300	Low elevation E–W bands of NLC seen in Denmark; varying brightness. At 2140 rapid changes of form and brightness then fading by 2215, at which time new formations appearing. (Photographs 2120, 2123.)	56°N 10°E	2105	7	345–360
				2215	4	360
2/3 Aug.	2145–2200	Extensive faint wave structure NLC above low tropospheric clouds.	59°N 09°E	2145	80	360
3/4	2145–2200	NLC veil to high elevation.	59°N 09°E	2145	80	360
4/5	0100–0200	Thin bands of NLC E–W seen overhead, receding to 40° elevation at 0200.	59°N 03°W	0100	90	
				0200	40	360–045
6/7	2200–2400	Possible NLC low N.	58°N 06·5°W			
			56·5°N 07°W			

TABLE II—ADDITIONAL REPORT OF NOCTILUCENT CLOUDS OVER WESTERN EUROPE DURING 1974

Date—night of	Times UT	Notes	Station position	Time UT	Max. elev. degrees	Limiting azimuths
20/21 June	2300–0045	Suspected display increased to become bright band and whirls at 2330 and intensely bright band at 2340, and fading to barely visible veil which extended to high elevation at 0030. Series of colour and black-and-white photographs 2330–0018.	55·5°N 04·5°W	2330	13	315–335
				0015	20	310–360

The 38 noctilucent-cloud appearances listed for 1975 include a larger than usual number of 'single-station' reports. All were from experienced observers, some accompanied by photographs, and all have been included in the list. During the year the longest unbroken series of displays was recorded in mid June; in 1974 this occurred in July.* Since northern stations were then

*MCINTOSH, D. H. and HALLISSEY, MARY 1975 Noctilucent clouds over western Europe and the Atlantic during 1974. *Met Mag*, 104, pp. 180–184.

experiencing almost continuous daylight the reports were received from central Scotland and further south—the exception being Aberdeen (57°N) on 14–15 June when diffuse forms were seen to cover the entire northern sky around 0030 h. During the period, only the displays on 12/13 and 14/15 June were seen to spread to any great extent.

Two widely reported displays on 28/29 June and 4/5 July were notable because they were bright enough to be seen from Lerwick during the short period of twilight there. On each occasion, too, the cloud field was extensive, visible in Norway and Denmark as well as over the length and breadth of the United Kingdom and Ireland, and showed the full panoply of bands, ripples, billows and veil. Photographs of these displays are available.

Appearances of the clouds from 6 to 9 July were seen only from the west of Scotland. They were not bright, but structure was discernible.

On 17/18 July NLC was seen from latitudes 55–56·5°N from Denmark, western Scotland and mid Atlantic. The observer from this last position was interested to know why he should be flying under this bright-banded cloud just one year since last seeing a similar phenomenon. The cloud observed from Denmark on this night was not seen above 12° elevation, but colour prints clearly show the cloud structure.

Three further displays between 21 July and 1 August were seen from Denmark and one from northern Scotland. The NLC by this time was appearing well to the north. Assuming a height of the cloud field of around 80 km, an observer in Denmark ventured an estimate that the cloud would be, at nearest, 500 km distant. This makes reasonable the inclusion in the list of three reports of the cloud for the nights 2–4 August. The reports, made from observing points at latitude 59°N—one station in Scotland and one in Norway—relate to cloud at high elevation, and were at first regarded as 'doubtful' observations.

One further possible display occurred on 6/7 August. The 'glow' reported from stations in west and north-west Scotland to be low in the north is thought likely to have been a sighting of NLC, aurora having been ruled out as a possibility.

Tropospheric clouds were as great a factor of obstruction to observation as in previous years, and there was at times the additional hazard of some fog and haze. There were, fortunately, few nights when completely cloudy conditions prevailed in all areas, and we pay tribute again to observers who are able to identify NLC through relatively small gaps in lower clouds.

We gratefully acknowledge the help of the many observers who have contributed the reports, sketches and photographs used in the compilation of this summary, and also the receipt of a Meteorological Office grant which enables the work to be carried out. Although the collection and publication of reports of visual aurora by this Department of Edinburgh University ended in 1975 we hope to be able to continue to receive and publish NLC reports for some further years.

NOTES AND NEWS

Retirement of Mr R. A. Buchanan

Mr Robert Andrew Buchanan, who retired on 31 May 1976, joined the Office in September 1939 after spending four years at Glasgow University, where he obtained an honours degree in Mathematics and Natural Philosophy. He

was also active in the University's Officers' Training Corps. After initial training he served during the earlier war years at Abbotsinch and H.Q. 18 Group RAF (Pitreavie), and in the autumn of 1942 was posted to Sullom Voe. He received a commission as a Flight Lieutenant in the Royal Air Force Volunteer Reserve in April 1943, and in June of that year was gazetted as Squadron Leader and posted to the Azores. He served in that area for the next two years and on his return to the United Kingdom went to H.Q. 13 Group (Inverness) from August 1945 until early 1946 when he was demobilized from the RAFVR. He then went to Washington, D.C., for an important and taxing job in liaison and co-ordinating work for meteorological services for the Allied Forces—a job which, although difficult, was very much to his liking. On return to the United Kingdom in 1947 he went to Dunstable, where he did a long stint on the Central Forecasting Office Upper Air Roster until September 1953 when he was promoted to Principal Scientific Officer. He was then posted to Northern Ireland as Senior Meteorological Officer at Aldergrove, where he stayed until September 1959. He then joined MetO 17 (Defence and International) at Victory House, Kingsway, London WC2, and once more became involved in international work, which he enjoyed immensely and carried out very effectively. He moved with the branch to Bracknell in July 1961. He was transferred for a short time in 1966 into MetO 6 (Defence Services) before joining MetO 7 (Public Services) in February 1967; here he was primarily engaged in work connected with the need for, and application of, meteorological services in industry and commerce. His previous experience gained in the international sphere in liaison work and the ability to make personal contacts stood him in good stead for his work in MetO 7. Although the bulk of that work was directed towards national interests he also retained some interests and responsibilities in the international field by serving on the World Meteorological Organization Executive Committee Panel on Development and Application of Meteorology to Economic and Social Problems. He also contributed to the planning and international work in the early 1970s which led to the European Centre for Medium-range Weather Forecasts which was established at Bracknell in 1975.

In 1973 he was promoted to Senior Principal Scientific Officer and posted to H.Q. Strike Command at High Wycombe as Chief Meteorological Officer. From personal acquaintance and friendship over many years I know that Mr Buchanan has had an interesting career and that his work and achievements, especially in the international field, have given him much personal satisfaction and a deservedly wide circle of friends.

Many of his contemporaries also know his wife Mary, either through her work in the Office in the 1940s when she was for a while Personal Secretary to the late Mr E. Gold, or later because she often accompanied her husband on his international visits. Their numerous friends will wish Robert and Mary a long and happy retirement and hope they enjoy good health to enable them to follow their many interesting activities for many years.

N. BRADBURY

THE METEOROLOGICAL MAGAZINE

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NOTICES

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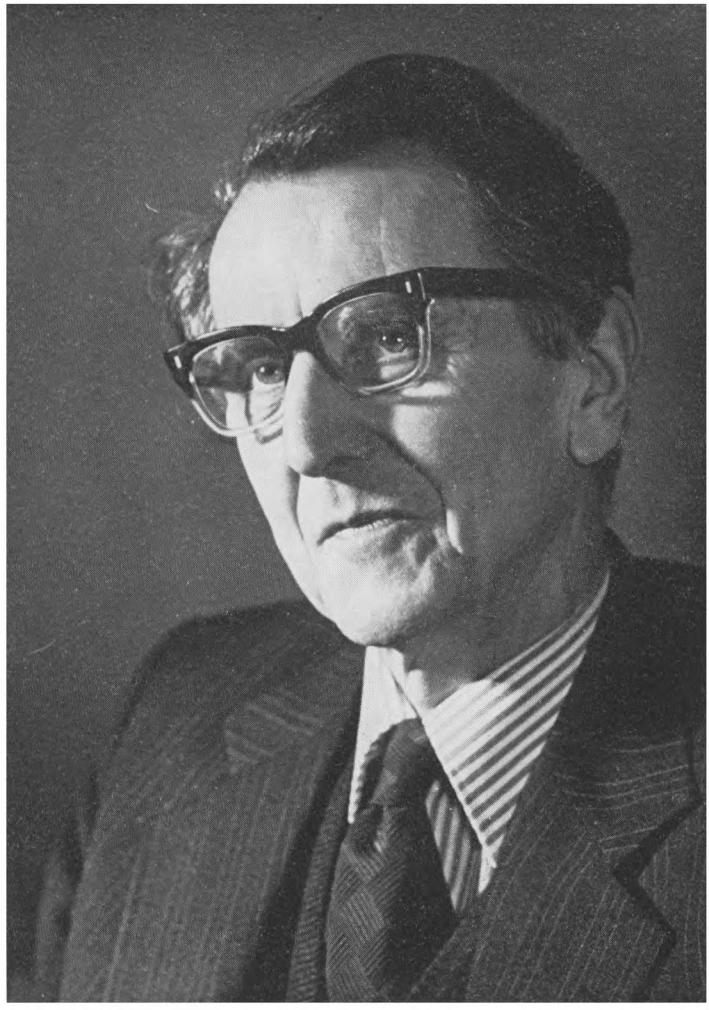

Photograph by A. C. Best

MR J. S. SAWYER, F.R.S.

METEOROLOGICAL OFFICE Met.O.893

THE METEOROLOGICAL MAGAZINE

Vol. 105, No. 1248, July 1976

RETIREMENT OF MR J. S. SAWYER, F.R.S.

On the retirement of Mr J. S. Sawyer as Director of Research on 19 June 1976, the Meteorological Office lost its most distinguished scientist and one who, over more than a decade, has exerted immense influence on his Directorate composed of powerful research teams working on most of the major problems of meteorology. Few have made such a wide and deep study of the whole subject as John Sawyer who has an unrivalled understanding of atmospheric behaviour and a profound feeling for the significant problems and of the difficulties that may delay their solution. This insight and knowledge, together with his objectivity and superb judgement, have enabled him to provide the necessary leadership and firm guidance for our many extremely able and ambitious young scientists and, while giving them a good deal of freedom in execution, he has never allowed them to lose sight of the main targets and priorities.

Mr Sawyer's personal researches, mainly devoted to analytical and theoretical investigations of the structure and dynamics of weather systems ranging in scale from lee waves to the global circulation of the atmosphere, have always been motivated by a keen awareness of practical problems and a strong desire to improve standards of weather forecasting. After serving for nine years as a forecaster in the United Kingdom and in South-east Asia, he played a key role as a research scientist in pioneering numerical weather prediction in the Meteorological Office. His seminal paper with F. H. Bushby, 'A baroclinic model atmosphere suitable for numerical integration', published in the *Journal of Meteorology* in 1953, laid the foundations for the first fully operational, three-level baroclinic model. He was also responsible for initiating the development of the first operational ten-level primitive-equation models operating on both hemispheric and fine-mesh grids which provide the basis of operational forecasting in the Meteorological Office for up to three days (recently six days) ahead.

Among his long list of publications on synoptic meteorology, his early papers on the theory of tropical cyclones and on the structure of the intertropical front over north-west India, published in 1947, his outstanding analysis of the structure and circulation of fronts published in 1956 and 1958, and his Presidential Address to the Royal Meteorological Society in 1964 on 'Meteorological analysis' deserve special mention. Mr Sawyer took advantage of the Meteorological Office's first computer to carry out, with G. A. Corby, a series of important theoretical studies of airflow over mountains, gravity waves and problems arising in the numerical solution of the dynamical equations. These

outstanding achievements were recognized by his election to Fellowship of the Royal Society in 1962 and by his Presidency from 1963 to 1965 of the Royal Meteorological Society, which awarded him the Hugh Robert Mill Medal in 1956, the Buchan Prize in 1962 and the Symons Memorial Gold Medal in 1971. In 1973 the World Meteorological Organization awarded him its highest honour, the IMO Gold Medal and Prize, for his outstanding contributions to dynamical meteorology and to international collaboration in meteorology.

Although John Sawyer never seeks the limelight and does not enjoy travelling, hotels, and international conferences, he has responded generously to the many calls on his time by national and international bodies seeking his advice and help. In particular he has been a member of the Joint Organizing Committee for GARP since its inception, was Vice-President of the WMO Commission for Atmospheric Sciences from 1961 to 1968 and President from 1968 to 1974. At home, he served as Editor of the *Quarterly Journal of the Royal Meteorological Society* from 1959 to 1961, as Chairman of the British National Committee for Geodesy and Geophysics from 1966 to 1972, and he has been Chairman of the Royal Society Committee on GARP since 1974. In all these tasks, his deep understanding of the scientific problems, his sound judgement and impartiality and, above all, his extraordinary personal modesty, have earned him the respect, affection and gratitude of meteorologists everywhere. It has been a privilege and a pleasure to work closely with him during this most exciting decade of meteorological advance.

Mr Sawyer's knowledge and advice will be greatly missed, but his colleagues will be glad to know that he will continue to serve on the Council of the Natural Environmental Research Council, on the Scientific Advisory Group of the European Centre for Medium Range Weather Forecasts, and on Royal Society and Meteorological Office committees.

We wish him and Mrs Sawyer a long and happy retirement in their new home in the West Country.

B. J. MASON

551.507.321.2

SOME ASPECTS OF THE SWINGING OF BALLOON-BORNE PAY-LOADS

By R. E. W. PETTIFER and R. G. FLAVELL

SUMMARY

Detailed analysis of the output record of a simple photo-electric attitude sensor has revealed considerable information about the swing behaviour of small pay-loads carried by single balloons. Earlier findings that slow rates of ascent (less than 2 m/s) are correlated with small swing amplitudes are confirmed and evidence is presented that marked changes in the nature of the package swing are correlated with passage through wind-shear layers.

A twin-balloon rig incorporating a reliable cut-off device for one balloon has been developed and tested and it is concluded that with such a rig large-amplitude swinging is eliminated even for rates of ascent as high as 6 m/s.

Introduction

There are many experiments in atmospheric physics that involve the use of light-weight simple, balloon-borne apparatus and for which a knowledge of the swinging characteristics of the pay-load is either essential or, at least, useful. In most such cases the use of elaborate attitude-sensing devices such as magnetometers or gyroscopes is ruled out by considerations of expense or of weight.

Recently (1974) Foot, Simmons and Whittaker* (hereinafter referred to as FSW) briefly described a simple photo-electric attitude sensor and discussed the results of a flight in which the sensor was used to indicate the extent of the swinging of the pay-load beneath a balloon. The work described in this report was an extension of that done by FSW, and employed an almost identical sensor. It was done as part of a program aimed at developing a suitable ballooning technique for flying an infra-red radiometer for spectroscopic measurements of stratospheric constituents. For this purpose it was necessary to have a fast initial rate of ascent and then, above 15 kilometres, an observation period when, whatever the rate of ascent, the swing of the package was less than 2° on either side of the vertical.

Initial work was done by using single-balloon rigs and the FSW sensor and from this it was found that by careful analysis and the use of a simple calibration technique, considerable information about the pay-load motion could be obtained. The correlation found by FSW between slow rate of ascent and small swings was confirmed but we do not confirm their conclusion of a lack of correlation between pay-load motion and wind shear. An improved balloon rig using two balloons was developed and the results of this technique are discussed below.

The theory of the photo-electric attitude sensor

The basic theory of the sensor has been described by FSW and they show that a solar cell, screened by an opal glass diffuser, will have, for incident sunlight, a response that is approximately proportional to the cosine of the angle of incidence. By using a simple relation between the angular excursion of the package, the solar zenith distance, and the output of the solar cell, FSW avoided the need for sensor calibration. However, the deductions that they made from their recorder traces were very limited and the simple calibration procedure discussed below allows a much more detailed interpretation of the swing information.

The basic geometry for the motion of the package is shown in Figure 1: θ is the zenith distance of the sun; γ is the angle between the plane containing the zenith, the balloon and the sun and the plane containing the zenith, the balloon and the package; α is the instantaneous swing amplitude of the package and δ is the angle between the sun's ray and the normal to the sensor (which is mounted horizontally on the upper face of the package). It can be shown by the application of the spherical cosine rule that

$$\cos\delta = \cos\theta\cos\alpha + \sin\theta\sin\alpha\cos\gamma \qquad (1)$$

and from this equation the sensor output corresponding to any regular oscillatory motion of the package can be predicted.

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* FOOT, J. S., SIMMONS, E. L. and WHITTAKER, A. E.; Measurements of the swing of a balloon payload. *Met Mag, London*, 103, 1974, pp. 110–115.

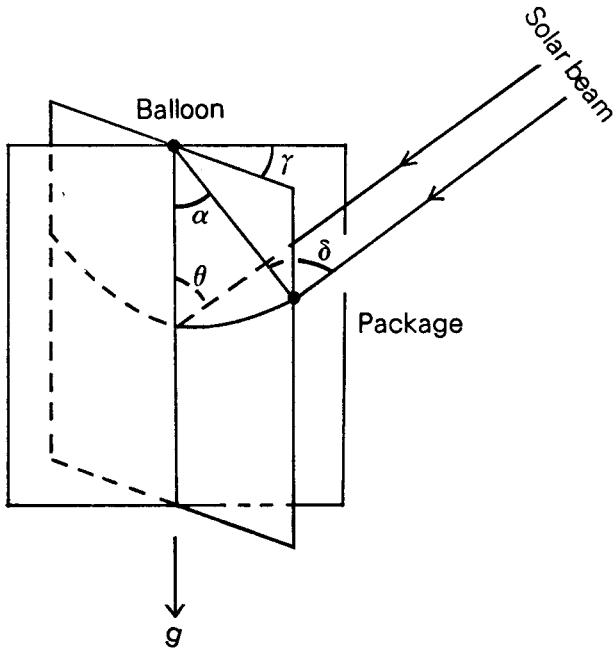

FIGURE 1—THE GEOMETRY OF THE PACKAGE IN FLIGHT

SENSOR CALIBRATION

The sensor output appears as a continuously varying voltage. For radio-transmission purposes this was converted into a modulation frequency and then, after reception, re-converted to a voltage and displayed against time on an XT pen-recorder. Provided that the pen recorder has a linear response it is possible, and convenient, to work in terms of recorder scale-divisions, so that a calibration of α against recorder scale-point is required. During a flight lasting 2½ hours the solar zenith distance changes (by about 16° between 1400 and 1600 GMT in June at latitude 50°N, for example) so that the scale reading arising when the package is vertical ($\alpha = 0$) will also change. Therefore, a calibration curve of scale-reading against the cosine of angle of swing, for swings in the plane containing the balloon and the sun (i.e. $\alpha = 0$) may be obtained by assessing, from the recorder trace, those times at which the package was vertical and determining for them the recorder scale-reading, and, from astronomical tables, the solar elevation.

We considered the package to be vertical at the mid point of small symmetrical excursions of the recorder trace. The restriction to small amplitudes is necessary because of the inherent non-linearity of the cosine function. Two additional calibration points may be obtained before the balloon is launched, although they were not available for FSW's flight. By pointing the sensor directly away from the sun, the scale-point corresponding to $\delta \geqslant 90°$ may be found and by pointing directly at the sun the $\delta = 0$ point may also be found. Owing to the presence of cloud or haze, this last point cannot always be obtained but this does not detract seriously from the usefulness of the method.

Figure 2 is the calibration curve for FSW's data, derived by the method discussed above; the line is a least-squares fit to the points. The large scatter seems to have been due to instability in the electronics of the transmitting/receiving system. Our subsequent flights with more stable electronics have yielded calibration curves with much less scatter than is shown in Figure 2.

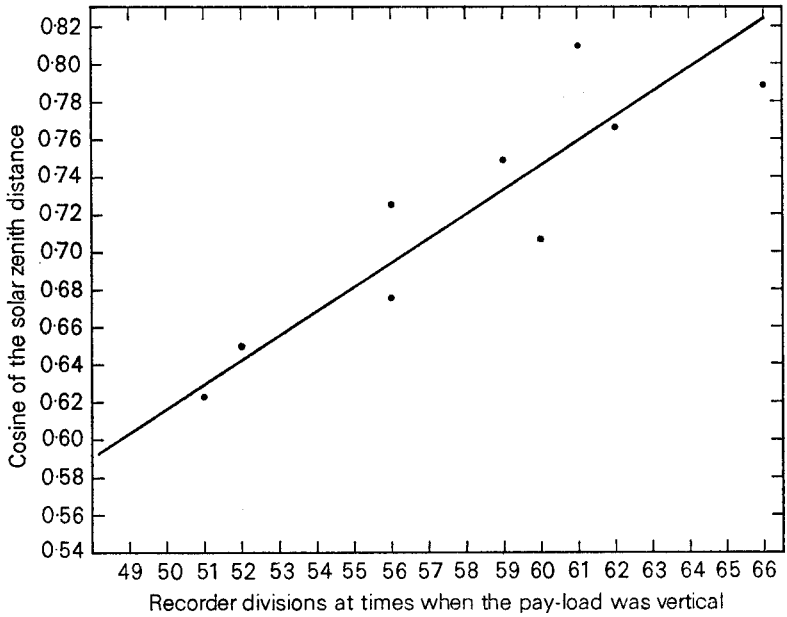

FIGURE 2—THE SENSOR CALIBRATION DERIVED FROM THE FLIGHT TRACE

Data analysis

A particular weakness of the analysis presented by FSW and one not explicitly stated in their text is that the angular amplitudes which they calculate are those appropriate to the component of the total swing that lies in the plane containing the balloon and the sun. They make no attempt to assess the most important parameter, namely the amplitude of the total swing. Even where the sensor output is almost constant, it is not obvious whether this is due to small swings or to swinging (of much larger amplitude) in a plane perpendicular to that containing the balloon and the sun. To illustrate how the technique that we report helps to overcome some of these ambiguities, we analyse below part of the original trace obtained by FSW and discussed by them. Traces that we have obtained by using the sensor and by using single-balloon rigs are very similar.

Figure 3 shows parts of FSW's sensor trace between about minute 60 to minute 63 (their Figure 2); several features of the trace are quite evident. The most obvious among these is a regular oscillation of period about 10 seconds with a definite, but not completely regular, low-frequency modulation; in addition there is the apparent halving of the high-frequency period that occurs at the minimum in the recorder excursions around minute 61·4.

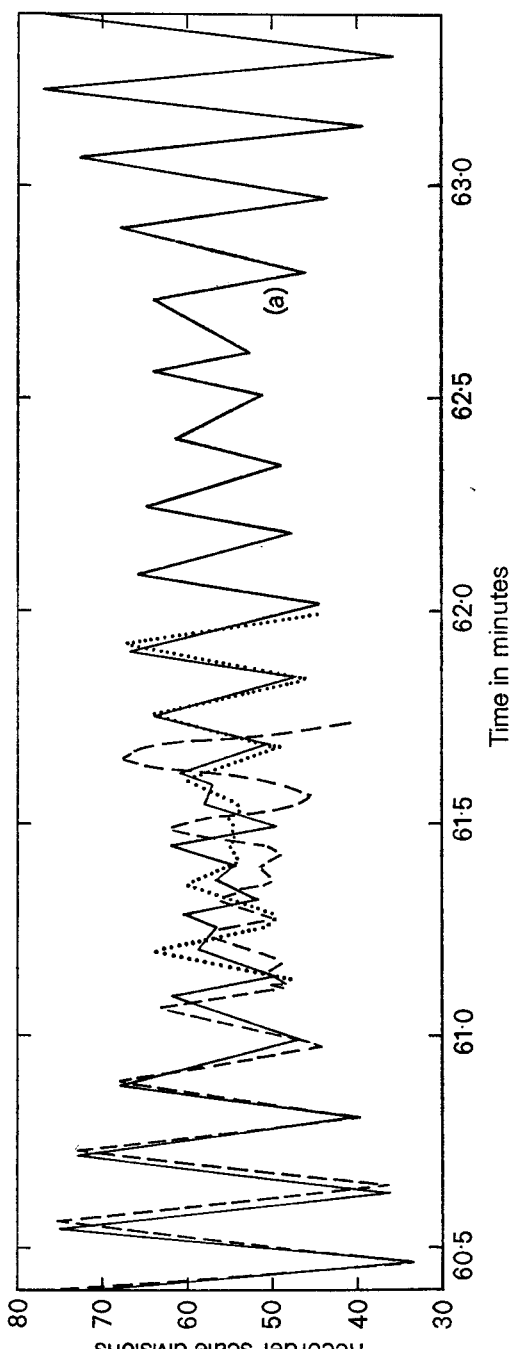

FIGURE 3—PART OF FOOT, SIMMONS AND WHITTAKER'S ORIGINAL FLIGHT TRACE (TIME-SCALE EXPANDED) WITH THEORETICAL TRACES SUPERIMPOSED SHOWING PRECESSING PLANAR SWINGING

——· Flight trace
– – –· Theoretical trace: amplitude ± 28°, precession rate 1·45°/s
. . . . · Theoretical trace: amplitude ± 12·5°, precession rate 2·3°/s

To a first approximation, the most reasonable interpretation of this low-frequency modulation might be that the package was executing an oscillation of constant amplitude, the plane of which was precessing steadily relative to the plane containing the balloon and the sun (the principal plane). If this interpretation is correct then the excursion of maximum amplitude is in, or very nearly in, the principal plane and will be approximately a measure of the maximum angular swing of the package and this can be found from the calibration curve (Figure 2). Evidence that this is in fact the correct interpretation of the motion can be seen at the minimum-amplitude portion of the trace. Figure 4 shows the relative output of the sensor for sinusoidal oscillations of the package in a series of planes for a fixed solar zenith distance of 45° and a maximum swing amplitude of ±30°. For the plane perpendicular to the principal plane, marked 90/270, it shows a double maximum, an effect that will result in an apparent doubling of the frequency of the pen-recorder trace. Such a doubling is clearly evident at the minimum-amplitude part of the low-frequency oscillation of Figure 3 and we therefore conclude that at this time the package was swinging across the principal plane.

By assuming that $\gamma = 0$ at minute 60·4 and that $\delta \approx 90°$ at minute 61·4 the rate of precession is easily calculated to be about 1·5°/s for this interval. Superimposed on Figure 3 is the change of amplitude, calculated from equation (1), appropriate to a maximum swing amplitude of 49 recorder divisions and a precession rate of 1·5°/s. From the calibration curve (Figure 2) the swing amplitude of the package, assumed constant, was calculated as ±28°. The agreement between these curves is sufficiently good to allow us to conclude that we have established to a fair degree of accuracy the nature of the package motion over this part of the ascent.

It is clear from Figure 3, however, that the characteristics of the oscillation changed as the angle γ (Figure 1) approached 90°. If we apply the same analysis procedure to the interval from minute 61·25 to minute 62 as we applied to the earlier interval, we obtain a precession rate of about 2·3°/s and a maximum swing amplitude of about ±12½°. The theoretical recorder trace for such values, obtained from equation (1), is also shown in Figure 3 and although this does show a reasonable measure of agreement with the actual recorder trace in the large-amplitude section, no adjustment of the relative phase between the two portions of the calculated curve of Figure 3 can give a reasonable representation of the actual trace through the node of the low-frequency modulation around minute 61·25.

The third section of the actual trace, from minute 62·6 to minute 63·6, shows a very different pattern from the first two, especially in the 'nodal' regions. Notice particularly the 'stretching' of the period of the high-frequency half-cycle marked (a). It is not difficult to show from equation (1) that this feature is characteristic of elliptical swinging by the package, and in Figure 5 the second section of the flight trace is compared with the calculated trace for elliptical swings with a major axis equivalent to a swing angle of 12·5° and a minor axis equivalent to swing angle of ±4·3° together with a precession rate of about 2·3°/s. The fit is remarkably good up to minute 62·7. Thereafter, changes in amplitude (by about a factor of two), phase and precession rate (by about 25 per cent), shown by the second theoretical curve, are required to fit the remainder of the flight trace up to minute 63·4. We therefore deduce that around minute 61·3 the essentially precessing planar swings of the

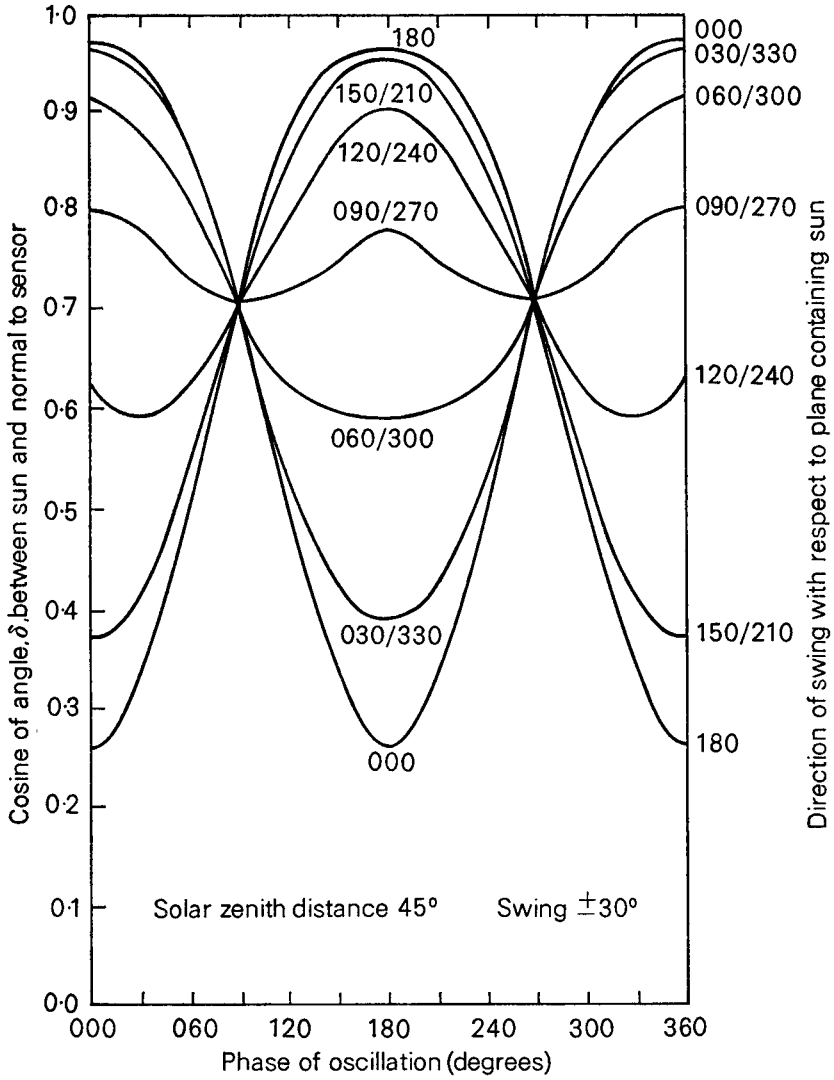

FIGURE 4—RELATIVE OUTPUT OF SENSOR FOR PLANAR SWINGS IN VARIOUS PLANES FOR $\theta=45°$ AND A MAXIMUM SWING AMPLITUDE OF $\pm 30°$

package changed to precessing elliptical swings and that around minute 62·6 these elliptical swings underwent changes of amplitude, phase and precession rate.

Figures 6(a) and 6(b) show respectively the wind speed at balloon height and the track of the balloon during this part of the flight. The direction of swing of the package and the wind direction at balloon height for the critical points during the period corresponding to the traces of Figures 3 and 5 are also shown. Clearly, between minute 61 and minute 62 and again between minute 62·5 and minute 63·0, the balloon passed through a wind-shear layer in which the perturbation of the balloon had a substantial component perpendicular

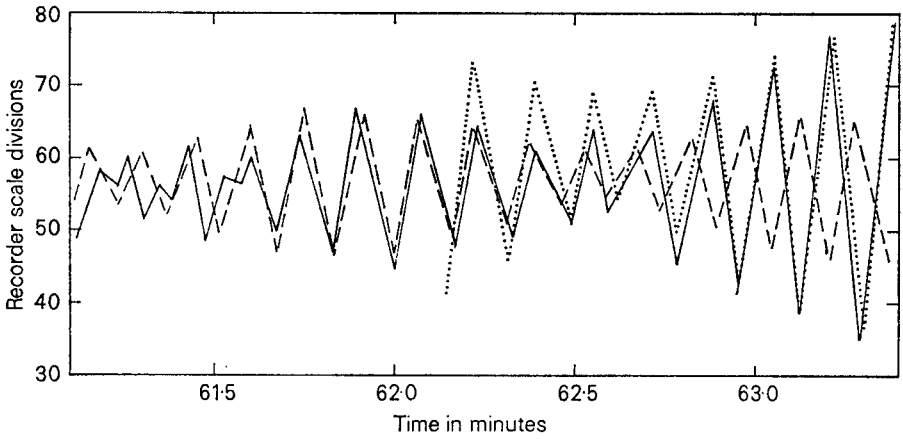

FIGURE 5—PART OF FOOT, SIMMONS AND WHITTAKER'S ORIGINAL FLIGHT TRACE (TIME-SCALE EXPANDED) WITH THEORETICAL TRACES SUPERIMPOSED SHOWING PRECESSING ELLIPTICAL SWINGING

·——· Flight trace
·– – –· Theoretical trace: amplitude ± 12·5° (major axis), ± 4·3° (minor axis), precession rate 2·3°/s
· · · · · Theoretical trace: amplitude ± 26·4° (major axis), ± 9° (minor axis), precession rate 1·7°/s

to the plane of the swing (digitization errors of about ±12·5 m in radar range will have a negligible effect on the calculated wind shears). We conclude, contrary to FSW, that wind-shear layers have a marked effect on the motion of the package; in these cases they induced precessing planar swings to change to precessing elliptical swings and then changed the amplitude and phase of the elliptical swinging. It is easily demonstrated in the laboratory that such changes in the character of the swing of a simple pendulum are consistent with motions of the suspension point across the direction of the swing of the bob.

THE TWO-BALLOON RIG

In order that total flight times should be realistic, due regard being given to radar-range and air-lane problems, it was necessary that the balloon-borne package to be used in our experiments should have a fast initial rate of ascent but that, in order to ensure swinging of very small amplitude during the observational period, the rate of ascent should be slowed to about 1·5 m/s. Various gas-venting techniques were tried in order to reduce the free lift of the balloon and to slow it down, but without the unacceptable penalty in load required by an elaborate, electronically controlled valve none of these proved to be sufficiently reliable. Accordingly it was decided to adopt a twin-balloon rig in which one balloon was the source of almost all the free lift. This balloon was cut free from the rig at a predetermined pressure by the use of a commercially available miniature explosive cut-off device known as a 'Nobel explosive guillotine' and the remaining balloon, having acquired increased positive free lift from the effects of solar heating, carried the package aloft at a much reduced rate of ascent. Several different release arrangements were tried. The two constraints were that the explosive guillotine would not accept a wire thicker than 20 SWG and therefore could not carry the suspension cable

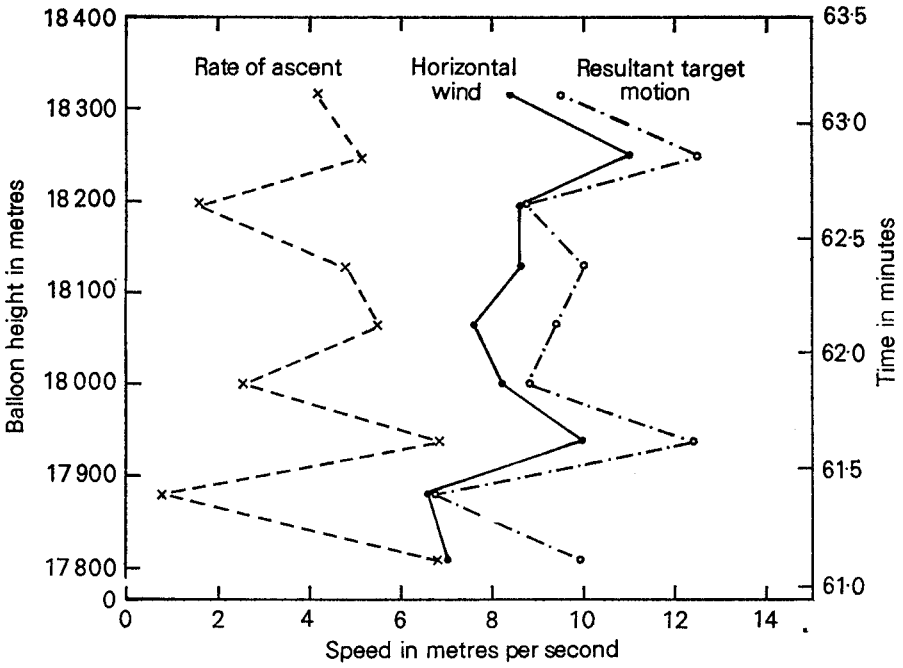

FIGURE 6(a)—RATE OF ASCENT, HORIZONTAL WIND SPEED, AND RESULTANT TARGET SPEED

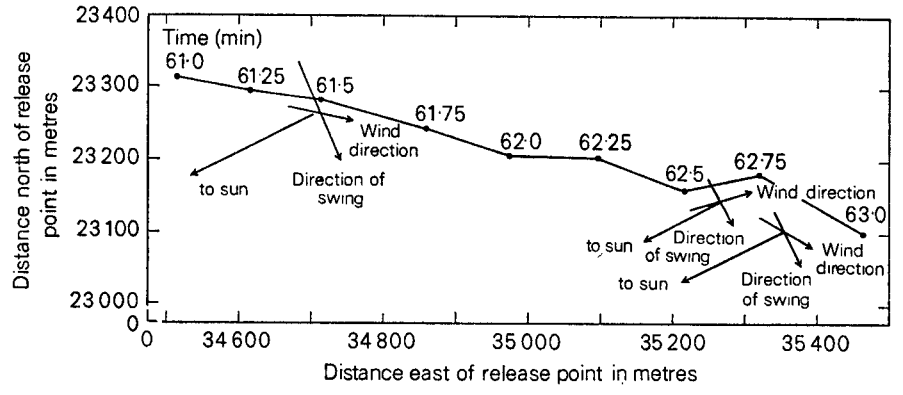

FIGURE 6(b)—THE BALLOON TRACE, PACKAGE SWING DIRECTION, AND WIND AT BALLOON HEIGHT

The OY direction indicates 'north' and the OX direction 'east'.

and the need to ensure that the cable of the released balloon did not foul the remainder of the rig. The solution adopted is shown in Figure 7. The guillotine cut a 26-SWG copper-wire retaining loop, thereby allowing the upper end of the 25-cm long alloy tube to fall away from the balloon cable. The upward motion of the secondary balloon then slid the tube smoothly through the fibre

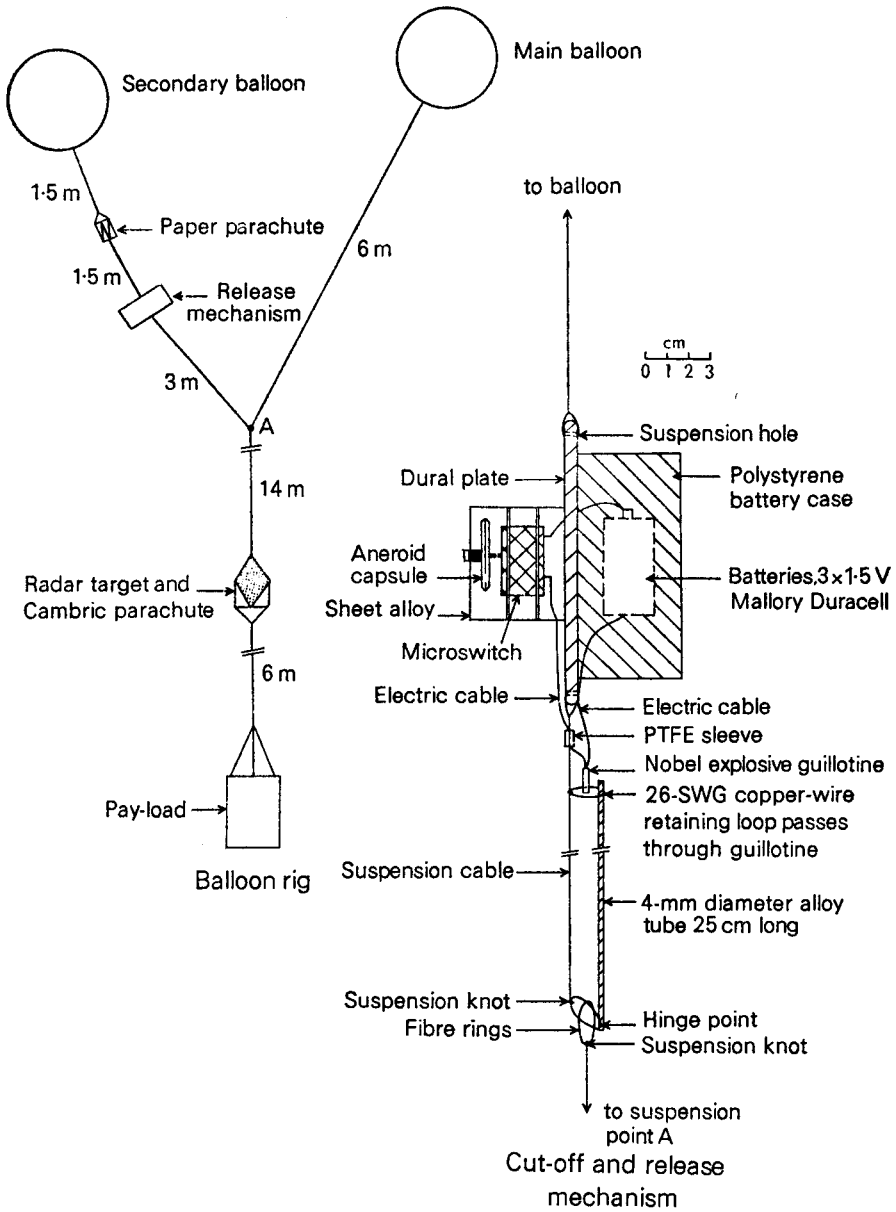

FIGURE 7—THE TWIN-BALLOON RIG AND CUT-OFF DEVICE

ring, parting the two sections of the rig with no danger of entanglement of the two cables. Full details of the rigs used are shown in Figure 7. The load on the main balloon was 5410 g, with a total unladen lift of 5600 g, yielding a free lift of 190 g. For the secondary balloon the equivalent figures were 780 g (comprising the cut-off device and parachute), 5000 g, and a free lift of 4220 g.

This system worked extremely well and reliably released the first balloon at about 100 mb, the pressure-activated cut-off having been preset to fire at this pressure. During the first phase of the ascent the two balloons were observed to rotate slowly round each other, occasionally banging together, but this did not seem to have any deleterious effect on their performance in terms of height reached at burst. As with the single-balloon rigs, once the rate of ascent dropped below 2 m/s the package swings were reduced to around $\pm\frac{1}{2}°$; the significant difference between the twin-balloon rig and the single rig was that for the twin rig visual observation of the package by several observers using a theodolite confirmed the conclusion drawn from the autographic record that, even at rates of ascent as high as 6 m/s, the package swing never exceeded $\pm 15°$ and was frequently less than $\pm 10°$. This is in contrast to single-balloon rigs, for which swings as high as $\pm 50°$ have been observed during fast-rate-of-ascent phases.

Figure 8 shows a typical portion of the output trace produced from the swing-sensor signal for the twin-balloon rig. The irregularities obvious in the single-rig case are not apparent and it does not seem possible to analyse this type of trace in the same way. An analysis of radar data similar to that given in Figure 6 for the single-balloon case showed the effects of wind shears on the motion of the package to be much less marked and there seemed to be a tendency for the resonances that appeared in the dynamics of the single-balloon rig to be damped out in the twin-balloon arrangement. The sharp spikes on the trace were caused by the shadows of the three symmetrical package-suspension strings passing across the face of the sensor as the package spun. From the period of these events the average spin rate can be deduced as approximately 0·5 rev/s.

Conclusions

We have shown that a very simple and cheap attitude-sensing device can yield quite detailed information about the motion of a balloon-borne package for the case of a single-balloon rig in which the motion is reasonably well behaved, although it should be made clear that even in this case there are likely to be some parts of the output record of the sensor that cannot easily be interpreted. We have confirmed the earlier findings of Foot *et alii* that, for single-balloon rigs, rates of ascent below 1·5 m/s are associated with small-amplitude package swings of the order of $\pm\frac{1}{2}°$ but we find that, at faster rates of ascent, marked changes in the nature of the swing behaviour can be correlated with the passage of the balloon through wind-shear layers. We have successfully flown a two-balloon rig incorporating a very efficient and reliable cut-off device to release one balloon and have observed that even at fast rates of ascent up to 6 m/s such a rig does not seem to allow package swing of more than about $\pm 15°$ for the rig dimensions used by us. However, the simple attitude-sensor used successfully on the single-balloon rig did not yield results that could be interpreted in detail when used with the twin-balloon flights.

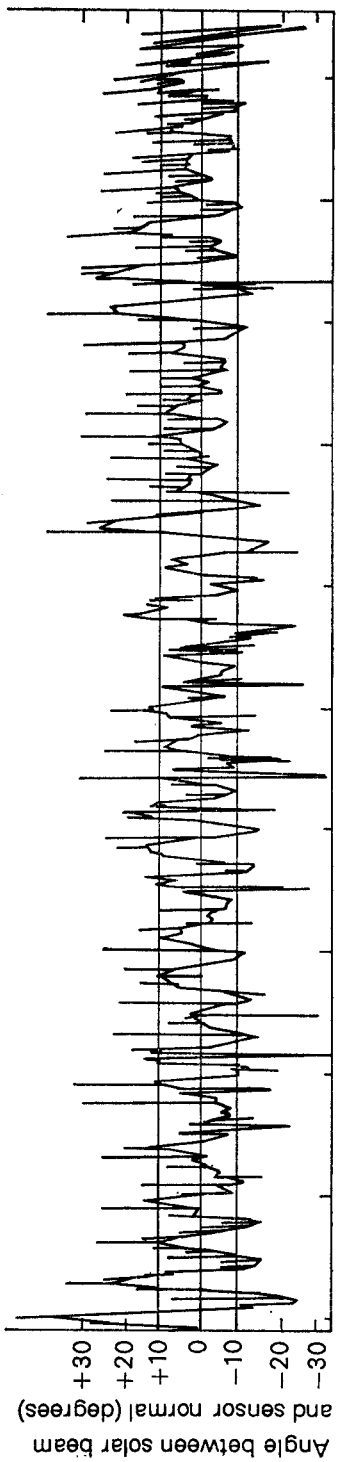

FIGURE 8—FLIGHT TRACE FOR THE TWIN-BALLOON RIG FOR A RATE OF ASCENT OF 6 m/s

ACKNOWLEDGEMENTS

Thanks are due to Dr E. L. Simmons for the loan of his original flight records and for helpful remarks and discussions, to Mr A. J. Thomas, who built the electronics for our sensor flights, to Mr D. E. Chapman who assisted with the calculations and to Mr D. E. Miller for helpful discussions.

551.509.314

A STOCHASTIC MODEL OF THE WEATHER AT HURLEY IN SOUTH-EAST ENGLAND

By P. R. EDELSTEN

(The Grassland Research Institute, Hurley, Berkshire)

SUMMARY

A stochastic model is described which produces a plausible sequence of daily climatic variables for Hurley in south-east England, using random-number generators. A Markov-chain model was used to produce sequences of days of similar weather. Regression analysis was used to obtain equations to predict other variables. The model was tested against the original data and found to work tolerably well, except that the sequencing model required some elaboration.

INTRODUCTION

Climate is the primary driving variable of an agricultural system; climatic variables such as rainfall and radiation determine the biological output from the system through their effect on crop growth and photosynthesis. In grazing systems, the effect on output is largely through herbage production and the quantity of forage available to feed animals. The climate also affects the way in which agricultural systems are managed; for instance, certain operations such as harvesting can only be carried out in favourable weather.

The Systems Synthesis Department of the Grassland Research Institute has, for several years, been involved in constructing simulation models of grazing systems. The author has developed a model of sheep production (Edelsten and Newton, 1975) which goes from herbage production through to the production of lamb carcasses for sale. This model has been used to compare the risks of different management regimes by running the model over a series of years to estimate the year-to-year variability in profitability. The main difficulty was that the herbage growth data used were only available for a 9-year sequence for one site, making the estimates of risk rather tenuous.

In order to be able to run grazing systems models over longer sequences of years and for different sites, it was decided to construct a herbage-growth model for use in the sheep model. The herbage-growth model was to predict herbage growth for a particular site, given inputs of climatic variables. This scheme is illustrated in Figure 1.

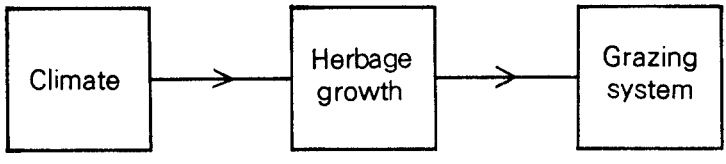

FIGURE 1—RELATIONSHIP OF CLIMATE MODEL TO GRAZING MODEL

The simplest way to enter climate data to the herbage model would be to use actual historic data; a magnetic tape of daily climatic data could be kept at the computer and read by models as required. The disadvantage of this approach is that one is limited to the amount of data available; at Hurley, for instance, we have only 16 years' data—not enough to make reliable estimates of the distribution of herbage production.

The alternative approach is to use a stochastic model which produces a plausible sequence of daily climatic variables using Monte Carlo random-number techniques. Such a model can be run over any time-period and can be easily adapted for site-to-site variability. Jones *et alii* (1970) and Dumont and Boyce (1974) have produced climate generators for similar purposes to those outlined above. Jones *et alii* produced daily values for rainfall, temperature and vapour pressure, but did not pay much attention to temperature sequences; Dumont and Boyce's climate generator produced daily values for rainfall, temperature, sunshine, wind speed and vapour pressure, but did not pay as much attention to correlation between the variables as was required in the present study.

Description of the model

The model generates values for the following climatic variables for each 24-hour period:

VARIABLES	UNITS	SYMBOLS
Rainfall	mm	R
Sunshine	h	S
Radiation	mW/cm^2	Z
Minimum temperature	degrees Celsius	T_{min}
Maximum temperature	degrees Celsius	T_{max}
Vapour pressure	mb	V
Wind speed	mile/d	W

(1 mile/d = 0·0186 m/s)

In addition, the following other conventions are used in the descriptions that follow:

R = rainfall today
R_{-1} = rainfall yesterday
R_{-2} = rainfall day before yesterday, etc.
d = day of year
q = quarter number (1st quarter = March–May
2nd quarter = June–August
3rd quarter = September–November
4th quarter = December–February)
k = sequence number (see *Sequencing* below)
s = relative sunshine (see *Sunshine* below)
r = random number between 0 and 1
D = day length in hours.

Sequencing

Hurley weather can be characterized broadly in terms of a series of fairly short sequences of days of similar weather, which could probably be most easily modelled in terms of wind direction and barometric pressure. However, data for these variables were not available and an attempt was therefore made to model the weather sequences in terms of temperature and rainfall, reasoning that weather sequences in summer are often either hot and dry or cold and wet,

while in winter they tend to be either warm and wet or cold and dry. Hot and cold are taken in this context to be relative to the seasonal mean temperature.

The approach taken was to use a second-order Markov-chain model to describe the sequencing of the weather as suggested by Feyerherm and Bark (1965, 1967). There were four possible states for each day:

Cold and Dry (CD)
Hot and Dry (HD)
Cold and Wet (CW)
Hot and Wet (HW).

A 'Cold' day was taken to be one when the mean of the minimum and maximum temperatures was below the seasonal average and a 'Dry' day was one when no rainfall was recorded, the lowest recordable rainfall being 0·1 mm.

Before estimating the transition matrices, the data were smoothed to make the sequences less noisy. Rainfall was smoothed by removing odd wet (or dry) days from sequences of three or more dry (or wet) days so that, for example, the sequence DDWDDWWDW would be smoothed to DDDDDWWWW. Temperature was smoothed by taking a 3-day moving average of the seasonally adjusted mean of minimum and maximum temperature. This made the sequences in the data stand out more clearly and defined the point of transition from one sequence to another more precisely. Weiss (1964) smoothed rainfall by taking a 'Dry' day to be any day when rainfall is below a certain threshold level, but this method seemed unsatisfactory for our purposes because the amount of rainfall is not highly correlated with the rainfall sequence. For example, in summer there is sometimes an isolated day of heavy rainfall in a long sequence of dry days, so that the day is essentially also a 'Dry' day in terms of its sequence type, even though it rained a lot.

The probability of a day being in a particular state was taken to depend on the states of the previous two days, using a second-order Markov chain. Seasonal variation was dealt with by dividing the year into four quarters corresponding to spring, summer, autumn and winter: March–May, June–August, September–November and December–February, and having a separate 16×4 transition matrix for each season, estimated from the data. The sequence k could then be generated by picking a random number r between 0 and 1 (Naylor *et alii*, 1966) and comparing it with the appropriate entries in the transition matrices.

Rainfall

Owing to the smoothing, it was necessary to introduce noise into the generated sequences. This was achieved by counting the numbers of wet and dry days taken out in the smoothing, giving the probability (P) of odd wet (or dry) days in sequences of two or more dry (or wet) days:

$$P \text{ (wet day in a dry sequence)} = 0{\cdot}09$$
$$P \text{ (dry day in a wet sequence)} = 0{\cdot}12.$$

Thus, to determine whether a particular day was actually dry or not, the sequence k was adjusted by comparing another random number r against one of these two probabilities.

Given that it rains, daily rainfall was assumed to come from a gamma distribution with parameters calculated from the original data for each month:

$$p(R) = \frac{\lambda^{\eta}}{\Gamma(\eta)} R^{\eta - 1} \exp(-\lambda R). \quad .. \quad .. \quad .. \quad (1)$$

Values were generated from the distribution using the method of Whittaker (1974).

Sunshine

Hours of sunshine were generated in two steps. Firstly, days when there was no sunshine at all were generated by using an extension to the sequencing model. The probability of zero sunshine was calculated for each season q and sequence k, and also according to whether or not there was zero sunshine the day before. This gave $4 \times 4 \times 2$ probabilities which were calculated from the data.

The second step was to generate the amount of sunshine for days on which this was greater than zero. Day length in hours was calculated from:

$$D = 12{\cdot}2 + 4{\cdot}35 \cos(\{d - 173\} \times 2\pi/365), \quad .. \quad (2)$$

where d = day of year, equation derived from Smithsonian Tables (1951). Relative sunshine $s = S/D$ was found to follow a truncated exponential distribution:

$$f(s) = be^{-bs}/(1 - e^{-b}), \ (0 < s \leqslant 1). \quad .. \quad .. \quad (3)$$

Values of b were calculated from the data for each season, sequence and whether or not there was any sunshine the day before by solving:

$$s = \frac{1}{b} - \frac{1}{e^{b} - 1} \quad .. \quad .. \quad .. \quad (4)$$

iteratively. Equation (4) was derived by applying the maximum-likelihood method to (3). Sunshine hours s could then be generated by using the transformation:

$$\begin{aligned} s &= D \times s \\ &= -D \times \log(1 - \{1 - e^{-b_{qkj}}\} \times r)/b_{qkj}, \quad .. \quad .. \quad (5) \end{aligned}$$

where b_{qkj} = parameter of distribution (3) for season q, sequence k and j set to indicate whether $s_{-1} > 0$,

and r = random number between 0 and 1.

Radiation

Solar radiation was found to be closely related to sunshine:

$$Z = Z_0[0{\cdot}195 + 0{\cdot}569s + (0{\cdot}029 - 0{\cdot}006s)\cos\{(d - 173) \times 2\pi/365\} + e] \quad (6)$$

where Z_0 = maximum radiation
$= 648 + 471 \cos\{(d - 173) \times 2\pi/365\}$
(from MAFF (1967) Table 12, page 74),
s = relative sunshine
and e = error term normally distributed with mean = 0 and standard deviation = 0·079.

Radiation was calculated by using equation (6), the error term being generated by the method of Box and Muller (1958).

Wind speed

Wind speed was found to be highly autocorrelated but showed little correlation with other variables, as in the study of Dumont and Boyce (1974). Wind speed was assumed to come from a gamma distribution (see equation (1)) with

$$\eta = \text{mean}^2/\text{sd}^2$$
$$\lambda = \text{mean}/\text{sd}^2$$

where

$$\text{mean} = b_0 + b_1 W_{-1} \quad .. \quad .. \quad .. \quad (7)$$

and standard deviation

$$\text{sd} = 45{\cdot}3 + 0{\cdot}000797\ \text{mean}^2. \quad .. \quad .. \quad .. \quad (8)$$

Values for b and b_1 in equation (7) were calculated by fitting the equation $W = b_0 + b_1 W_{-1}$ to the original data, for each sequence k and season q, using least-squares regression. Predictions of W using this equation were then grouped into classes and the mean and standard deviation of the predictions in each class calculated. Equation (8) could then be derived by regressing the standard deviations against the means.

Values for wind speed were generated by calculating η and λ from W_{-1} as shown above, and then generating a value from the gamma (η,λ) distribution in the same way as for rainfall (see *Rainfall* above).

Temperature

Minimum and maximum temperatures were autocorrelated and also correlated with other variables.

All the temperature data were seasonally adjusted to start with, using a seasonal trend function:

$$f(T) = T - 9{\cdot}65 - 6{\cdot}41 \cos(\{d - 206\} \times 2\pi/365). \quad .. \quad (9)$$

Equation (9) was derived by fitting a Fourier series to the mean of the minimum and maximum temperatures in the data.

Equations to predict adjusted minimum and maximum temperatures were then found by regression analysis:

$$T_{\text{min}} = a_{\text{kq}} + b_{\text{q}} T_{\text{min}_{-1}} + c_{\text{q}} T_{\text{max}_{-1}} + d_{\text{q}}(s + s_{-1})/2 + e_{\text{q}} W_{-1} + e_{\text{min}} \quad (10)$$

$$T_{\text{max}} = f_{\text{kq}} + g_{\text{q}} T_{\text{max}_{-1}} + h_{\text{q}} Z + i_{\text{q}} s + j_{\text{q}} W + e_{\text{max}}, \quad .. \quad .. \quad (11)$$

where e_{min} and e_{max} are normally distributed error terms. Values for temperature could thus be generated by using equations (9), (10) and (11), the error terms again being generated by the method of Box and Muller (1958).

Vapour pressure

Vapour pressure was closely related to temperature, but also affected by rainfall and radiation:

$$V = V_0(a_{\text{q}} + b_{\text{q}} Z + c_{\text{q}} R + e), \quad .. \quad .. \quad (12)$$

where V_0 = saturated vapour pressure

$$= 6{\cdot}03 + 0{\cdot}499T + 0{\cdot}00692T^2 + 0{\cdot}000571T^3 \quad (13)$$

(by polynomial regression on Table 94, page 352, Smithsonian Tables (1951)),

$T = (T_{max} + T_{min})/2$,

and e = normally distributed error term with mean = 0 and standard deviation = 0·107.

Testing the model

A computer program was written to generate the seven climate variables for each 24-hour period. A listing of the subroutines can be obtained from the author.

To test the program, a run of 100 years was made and the following statistics collected for each of the seven variables:

(i) daily means and standard deviations by month, quarter and year,

(ii) standard deviations of monthly, quarterly and annual means,

(iii) autocorrelations of lag 1, and

(iv) correlation matrices by month, quarter and year.

These statistics were then compared with the 16 years of actual data (9 years for radiation). It was recognized that such a comparison was an invalid test of long-term variability; however, the model was not constructed for use over the long term, the run of 100 years being used only to obtain good estimates of the variability produced by the model.

Means and standard deviations

Table I shows the daily means and standard deviations for the seven climate variables.

The quarters used to tabulate the data are January–March, April–June, July–September and October–December, not the seasonal quarters as used in *Sequencing*. The two sets of data correspond fairly well over the seven variables. This was to be expected since the distributions used ensure that the means and standard deviations converge for large enough samples.

TABLE I—DAILY MEANS AND STANDARD DEVIATIONS

	DATA Quarter				GENERATOR Quarter			
	1	2	3	4	1	2	3	4
Means								
Rainfall (mm d^{-1})	1·58	1·74	2·06	2·16	1·57	1·74	2·19	2·05
Sunshine (h d^{-1})	2·42	5·86	5·42	2·18	2·39	5·56	5·82	2·91
Wind (mile d^{-1})	129·26	121·55	107·81	127·92	129·16	123·01	111·93	122·62
Min. temp. (°C)	1·08	6·70	10·47	3·61	0·65	6·98	10·30	3·28
Max. temp. (°C)	7·83	16·40	20·16	10·70	7·59	16·42	20·18	10·83
Vapour pressure (mb)	7·24	10·55	13·92	9·13	7·04	10·57	13·56	8·90
Radiation (mW cm^{-2})	137·73	426·85	371·93	95·64	132·31	417·95	394·89	113·58
Standard deviations								
Rainfall (mm d^{-1})	3·11	3·91	5·21	4·19	3·03	3·95	5·36	4·19
Sunshine (h d^{-1})	2·85	4·36	3·80	2·56	2·93	4·69	4·64	3·05
Wind (mile d^{-1})	82·48	66·75	64·27	95·21	81·82	73·47	74·10	83·18
Min. temp. (°C)	3·79	3·76	3·10	4·54	3·64	4·00	3·21	4·14
Max. temp. (°C)	3·87	4·40	3·20	4·53	3·39	4·47	3·30	4·14
Vapour pressure (mb)	1·96	2·73	2·52	2·92	1·80	2·97	2·94	2·47
Radiation (mW cm^{-2})	112·28	184·59	164·95	75·36	106·37	199·92	197·75	88·22

Year-to-year variation

Table II shows that the generator produced year-to-year variations in quarterly and annual means for all the variables except wind that were surprisingly close to those in the original data. This was in contrast to the findings of Taylor (1972) who introduced a random variable to produce year-to-year variation in temperature. The reason why this study was more successful is that the sequencing model can produce sequences of values for a variable above or below the seasonal mean, and hence increase the standard deviation of year-to-year variation.

TABLE II—STANDARD DEVIATIONS OF THE MEANS FOR EACH QUARTER AND WHOLE YEAR

	Quarter				Whole year
	1	2	3	4	
Data					
Rainfall (mm d^{-1})	0·39	0·54	0·65	0·65	0·28
Sunshine (h d^{-1})	0·46	0·58	0·89	0·31	0·35
Wind (mile d^{-1})	18·88	17·15	20·54	42·76	18·47
Min. temp. (°C)	1·18	0·53	0·62	0·70	0·45
Max. temp. (°C)	1·28	0·95	1·30	0·65	0·78
Vapour pressure (mb)	0·49	0·58	0·65	0·40	0·36
Radiation (mW cm^{-2})	16·96	29·26	33·79	11·10	16·80
Generator					
Rainfall (mm d^{-1})	0·39	0·52	0·69	0·58	0·30
Sunshine (h d^{-1})	0·33	0·59	0·57	0·38	0·42
Wind (mile d^{-1})	19·31	14·54	16·53	19·34	12·84
Min. temp. (°C)	0·79	0·60	0·69	0·79	0·58
Max. temp. (°C)	0·81	1·00	1·09	0·84	0·91
Vapour pressure (mb)	0·44	0·64	0·77	0·57	0·75
Radiation (mW cm^{-2})	9·93	28·18	26·55	8·61	17·39

Autocorrelation of lag 1

Table III shows that the autocorrelation of rainfall, sunshine and radiation were too low compared with the data. This was because the only lag effects on these variables were those imposed by the sequencing model. To improve this aspect of the model we could either make the sequencing model more elaborate or put autocorrelation specifically into the model for rainfall and sunshine, as we did for temperature and wind.

I believe that it would be more fruitful to use the sequencing approach since this is the only way that the longer-term variations can be modelled.

TABLE III—AUTOCORRELATION COEFFICIENTS OF LAG 1

	DATA Quarter				GENERATOR Quarter			
	1	2	3	4	1	2	3	4
Rainfall	0·34	0·18	0·11	0·16	0·14	0·13	0·10	0·14
Sunshine	0·39	0·30	0·31	0·27	0·25	0·17	0·17	0·27
Wind	0·58	0·61	0·59	0·63	0·60	0·56	0·59	0·64
Min. temp.	0·68	0·59	0·47	0·72	0·61	0·60	0·44	0·70
Max. temp.	0·79	0·75	0·86	0·92	0·70	0·71	0·74	0·92
Vapour pressure	0·58	0·63	0·52	0·72	0·54	0·49	0·33	0·71
Radiation	0·60	0·35	0·53	0·60	0·49	0·21	0·32	0·55

Correlations

Table IV shows the correlation matrices for the real and generated data.

Most of the elements of the correlation matrices corresponded fairly well with those from the actual data, except for the following:

Rainfall and *sunshine*

Again, the sequencing model is to blame since all the correlation between rainfall and sunshine is through the sequencing model.

Sunshine and *minimum temperature*

Minimum temperature is largely dependent on clearness of the night sky. Sunshine hours were included in the temperature model on the assumption that high sunshine hours in the day-time should be correlated with a clear sky at night. This assumption does not seem to be borne out by the results, but there was nothing that could be done about this since night-sky clearness was not included in the data.

TABLE IV—CORRELATION COEFFICIENTS

	DATA Quarter				GENERATOR Quarter			
	1	2	3	4	1	2	3	4
Sun and Rain	−0·18	−0·28	−0·28	−0·23	−0·08	−0·08	−0·10	−0·09
Wind and Rain	0·20	0·07	0·13	0·16	0·13	0·09	0·08	0·11
Wind and Sun	0·04	−0·15	−0·14	−0·11	−0·06	−0·09	−0·09	−0·10
Min. temp. and Rain	0·14	0·11	0·09	0·04	0·12	0·07	0·04	0·09
Min. temp. and Sun	−0·16	−0·10	−0·24	0·01	−0·25	−0·14	−0·30	−0·15
Min. temp. and Wind	0·26	0·01	0·16	0·12	0·33	0·07	0·18	0·20
Max. temp. and Rain	0·11	−0·11	−0·19	0·09	0·05	−0·03	−0·11	0·01
Max. temp. and Sun	0·25	0·49	0·50	0·22	0·20	0·46	0·48	0·25
Max. temp. and Wind	0·24	−0·31	−0·23	0·05	0·24	−0·18	−0·18	0·02
Max. temp. and Min. temp.	0·55	0·52	0·29	0·68	0·46	0·51	0·18	0·59
Vapour pressure and Rain	0·18	0·11	0·07	0·11	0·16	0·08	0·04	0·12
Vapour pressure and Sun	−0·25	−0·08	−0·17	−0·07	−0·22	−0·09	−0·26	−0·08
Vapour pressure and Wind	0·21	−0·12	−0·04	0·05	0·31	−0·04	0·04	0·14
Vapour pressure and Min. temp.	0·73	0·74	0·62	0·79	0·77	0·75	0·64	0·80
Vapour pressure and Max. temp.	0·67	0·68	0·53	0·81	0·63	0·62	0·37	0·75
Radiation and Rain	−0·17	−0·22	−0·29	−0·23	−0·06	−0·06	−0·09	−0·06
Radiation and Sun	0·91	0·86	0·75	0·80	0·84	0·89	0·88	0·84
Radiation and Wind	0·09	−0·29	−0·15	0·03	−0·05	−0·10	−0·08	−0·12
Radiation and Min. temp.	−0·08	−0·19	0·08	0·23	−0·14	0·01	−0·17	0·12
Radiation and Max. temp.	0·43	0·39	0·67	0·47	0·36	0·57	0·55	0·53
Radiation and Vapour pressure	−0·15	−0·23	0·02	0·12	−0·13	0·01	−0·20	0·18

Conclusions

Evaluation of the climate generator depends on the intended application. For example, the model would be unsuitable for estimating the effect of climatic variability on future energy consumption since the limited data that the model was based on may be atypical of long-term trends. In addition, cross-spectral relationships between variables have not been fully explored, and regional climatic variations may make the structure of the model invalid for use over a wider area. However, tests indicated that the model may be suitable for limited applications such as the evaluation of the short-term viability of an agricultural enterprise at a specific location.

Improvements are necessary to the sequencing section of the model but the limited climatic data available for Hurley will make this difficult. Already, some of the elements in the transition matrices have been estimated from less than 10 events, and any attempt to enlarge the transition matrices to include other types of event would make the estimates of probability even more unreliable. One way round this problem might be to use periodic functions as suggested by Feyerherm and Bark (1965).

It should be easy to adapt the climate generator for use in other localities, simply by re-estimating the parameters using data from the area. However, it may be necessary to check the assumptions used in the model if the climate at the locality is very different from that at Hurley.

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REVIEWS

Clouds, rain and rainmaking, by B. J. Mason. 220 mm × 145 mm, pp. viii + 189, *illus.*, Cambridge University Press, Bentley House, 200 Euston Road, London NW1 2DB, 1975. Price £4·95.

The second edition of this well-known book follows its predecessor after an interval of 13 years.

The original selection and ordering of topics are retained in the new edition: cloud forms and features; the nuclei of cloudy condensation; the growth of cloud droplets; the germination and growth of snow crystals; snow, rain and hail; rainmaking experiments; the electrification of thunderclouds. These chapter titles indicate that the author's concern lies almost entirely with the microphysics of the various processes—a suggestion amply confirmed by the detailed text. Thus synoptic aspects of the formation of cloud, precipitation and thunderstorms are only very briefly discussed; while cloud dynamics, though acknowledged by the author to be very important and handled surely by him, are likewise cursorily dispatched.

This is intended to be by way of comment rather than of criticism. A wealth of data is presented relating to the constitution and formation of clouds and to the development within them of precipitation elements and lightning. These data refer both to laboratory experiments made under condition of careful control and to measurements in the 'real' atmosphere where observational methods have included the use of instrumented aircraft and ground radar. The author's main concern is to set the data in their physical and (where applicable) mathematical context, to describe both the relevance and limitations of laboratory experiments to the atmosphere, and to indicate the 'grey' areas of present knowledge and the nature of the barriers to future progress. He achieves this with an economy and fluency of presentation and style which make the book very readable. Its appeal is enhanced by its many fine plates (mostly the same as in the first edition but now distributed throughout the text, at appropriate points, instead of being grouped near the middle), and by an augmented list of simple illustrative experiments.

There are some points at which conciseness may be argued to have been carried too far. Thus the equation 3.1, which is an expression for the time rate of change of mass of an individual cloud droplet due to diffusion of water vapour, is neither obvious from first principles nor does it follow from the text which precedes it. The serious student has reason to pause at such a point and may be forced to refer to the author's more comprehensive text *The physics of clouds*. Specific references to the latter book, or to original sources, are given for various other mathematical derivations.

The newer work reported in this edition is mainly on ice nucleation, hailstone structure and growth, experiments in rainmaking, and the electrification of thunderstorms. These jointly pose the most difficult problems in cloud physics and, not unnaturally, are also those which arouse most controversy. This is not a new situation for thunderstorm electrification—witness, notably, the controversy of the inter-war years between G. C. Simpson and C. T. R. Wilson. The author has been especially active in this field of investigation and devotes much of the book's final chapter to the proposition that the formation and

growth of hail pellets is the primary mechanism of charge separation. Recent correspondence in the meteorological literature suggests that this is a controversy which is unlikely to be settled in the near future.

D. H. MCINTOSH

Environmental data from historical documents by content analysis: freeze-up and break-up of estuaries on Hudson Bay 1714–1871, by D. W. Moodie and A. J. W. Catchpole. 150 mm × 230 mm, pp. xviii + 117, *illus.*, Department of Geography, The University of Manitoba, Winnipeg, Canada R3T 2N2, 1975. Price: $4.

This book describes the procedure used to derive the dates of freezing and thawing of estuaries around Hudson Bay from entries in the records of the Hudson's Bay Company over the period from 1714 to 1871.

It is a very worthwhile enterprise but the description of how it was done makes the dreariest reading imaginable. The oppressive verbiage and mostly unnecessary jargon are exceptionally tiresome to read; in the end the authors admit that what is not precise remains imprecise, and that probabilities have to be handled by arbitrary assumptions.

There is an account of the reliability testing which shows that any errors in the final derivations from the journals arise much more from the imprecision of the content than from the subjective judgment of the interpreters.

In three tables at the end are listed the first date of freezing, the date of final freeze-up and the first date of break-up in the spring for six locations around Hudson Bay from 1715 to the middle of the 19th century. Judging from the tests described in the book, the first dates of freezing and break-up should be reliable enough to assist climatic-change studies of this singular area of the northern hemisphere.

M. K. MILES

A short course in cloud physics (*International Series in Natural Philosophy, Volume 84*), by R. R. Rogers. 205 mm × 125 mm, pp. xii + 227, *illus.*, Pergamon Press Ltd, Headington Hill Hall, Oxford OX3 0BW, 1975. Price: £6·50.

This book is based upon the author's lecture notes for the thermodynamics and cloud physics parts of a graduate course in physical meteorology at McGill University. Therefore naturally, but somewhat unusually for cloud physics texts, the first chapters deal with the thermodynamics of dry and moist air. The concepts of stability and buoyancy are developed from this base and applied to the convective process. The reader is led gently from elementary parcel theory to the modifications necessitated by mixing and aerodynamic resistance.

The development of the theory of droplet growth in non-freezing clouds follows the classical pattern from nucleation, through condensational growth, to coalescence. Then the formation and growth of ice crystals is described in a similar manner before the relevance of these processes to rain and snow formation is assessed.

The subject of cloud dynamics is introduced through a description of the instrument whose use has led to many of the advances in this topic, namely weather radar. This is followed by a short account of the structure and dynamics of precipitation-forming processes ranging from widespread frontal systems to severe convective storms.

The book ends with a brief, qualitative introduction to weather-modification principles, and an account of the fundamentals of cloud modelling. The latter is useful in describing the physical advantages and limitations of some of the possible approaches to the subject. A short bibliography containing references up to 1974 is provided.

The book, as a whole, is disappointing. It does not set out to be, and is clearly not, a major treatise on the subject. The wide range of topics covered, of necessity, leads to a certain superficiality in many areas, and when the author states 'In preparing this material I found it very useful to have at hand the books on cloud physics by Fletcher (1962), Byers (1965) and Mason (1971)', there is a distinct impression that the reader will find it equally useful, and even essential, to do the same. This criticism would be unimportant if the book provided the insights and new perspectives so difficult to achieve in the major works, engrossed as they often are with rigour and the desire for completeness. There is some evidence that Rogers had this in mind, but it is *not* a strong characteristic of the book. The provision of problems at the end of each chapter suggests that he was attempting to develop a quantitative 'feel' for the subject in his readers but even here the lack of accompanying answers to the problems does not encourage the beginner. The book does cover a wide field in a relatively simple quantitative manner but without great authority or novelty of approach.

P. RYDER

Physical and dynamic climatology (*Proceedings of the Symposium on Physical and Dynamic Climatology, Leningrad, August 1971*). 220 mm × 150 mm, pp. 400, *illus.*, World Meteorological Organization, Geneva, 1974. Price: 30 Sw. Fr.

The Leningrad symposium of 1971 was among the first at which the feeling that man's activities might be about to begin to affect global climate was discussed by meteorologists at an international level. Many of those present had strong opinions about the way things were going, and the question of what attitude the science should take in advising governments and peoples about the possible dangers ahead was never far from the minds of the participants.

Reading the proceedings of the symposium which have now been published, one's first thought is that they have been a long time coming, and that work that seemed fresh then is commonplace now after years in which the problems of pollution and climatic change have been discussed, popularized and vulgarized almost *ad nauseam*. Disappointment in the published papers is even

greater when it is realized how much of what was actually presented, and some of it the most relevant to the main topic, is absent, or presented only in the briefest form. This is perhaps inevitable when the issues are delicate, and authors are not necessarily willing to go as far in their written as in their spoken pronouncements; also, of course, many papers have since been published elsewhere and are therefore omitted here. What is left is a very uneven volume with no clear theme running through it. It covers a wide variety of topics ranging from the local climatology of showers to variations of climate on the largest time- and space-scales. Perhaps the main value to western meteorologists will lie in the Soviet contributions which can be read here without the tedium of translation. The papers by Gandin, Shvetz and Yudin, Sergin and Sergin, and Obukhov for example will repay study and indeed seem now of greater interest than the review papers whose relevance is much lessened by the passage of time.

A. GILCHRIST

NOTES AND NEWS

One hundred and twenty-five years ago*

Of late years much attention has been paid to Meteorological phenomena, with the hope of determining the laws by which the apparently inconsistent winds and the resulting weather are regulated. We have established observatories in all parts of the world in which records are kept of almost every passing cloud. The temperature of the air, the pressure of the atmosphere, the hygrometric state of the gaseous envelope, the electrical condition of it, the directions of the winds, and many other points of importance are registered under the direction of competent observers. From the results thus obtained, Professor Dove has already deduced some important facts, and determined the existence of fixed laws regulating at least some of the atmospheric phenomena.

Instruments have from time to time been devoted for registering the above points. Professor Whewell of Cambridge and Mr. Follett Osler of Birmingham, have devised very complete anemometers and rain-gauges; Mr. Osler associating also some other registrations with his very complete instrument. In the Hall of the Polytechnic Institution, and at the Philosophical Institution of Birmingham, an opportunity is afforded of examining what has been done, and of comparing it with the very complete "Atmospheric Recorder", of Mr. Holland, which registers every breeze that blows, or shower that falls, upon the Industrial Building in Hyde Park. Without drawings, it is quite impossible to describe, so as to be understood, the details of the arrangements. But some of its principles may be rendered easily intelligible. In the first place it will be understood that every fact is recorded by the machine itself, by means of a pencil passing over a regularly moving piece of paper, which is carried onward by an attachment with an eight-day clock.

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* From 'The Great Exhibition—London 1851'. The Art-Journal Illustrated Catalogue of the Industries of All Nations. London, Bradbury and Evans, 1851.

The barometer is of the siphon form, of large bore, and upon the mercury in the shortest leg is a float very accurately counterpoised, leaving only sufficient weight to enable it to follow the mercury in its rise and fall. It will be readily conceived that many plans might be adopted for connecting this with a pencil, which should mark every variation. The thermometric arrangement consists of ten mercurial thermometers, of a peculiar form, very accurately balanced, so that the slightest movement of the mercury gave at once a given degree of preponderance on one side or the other. A slip of wood is employed as the hygrometer; this is placed in a tube, through which the air passes freely; every elongation or contraction of this, indicating an excess or deficiency of moisture in the air, is in like manner registered. It will be, of course, understood that a piece of wood forms a very good hygrometer by absorbing moisture or parting with it readily. The electrometer is an insulated conductor, fixed on the highest convenient place, from which a wire is brought down to the instrument, and connected with a fixed disc, near which is fixed a moveable one. When a cloud charged with the electric fluid comes within range of the conductor, the moveable disc begins to slowly pass from the fixed disc to spring, discharging each time a portion of its electricity; it then falls back to the first disc, and remains quiet until another electric cloud approaches; the moving disc, carrying a pencil, records every disturbance.

The rain-gauge is placed on top of the building; it is a foot square. The rain collected in this passes through a pipe into the building, and a float indicates the height of the water and regulates the motion of the pencil. The amount of evaporation going on is by a similar contrivance registered. The direction of the wind is recorded by another pencil which marks the course upon the paper throughout the whole circle of the horizon, or that part through which it passes, and the force of the wind is indicated by the action of the aërial current upon a board one foot square fixed to the vane, and accurately counterpoised, so that the slightest pressure is at once indicated by the movement of the counterpoise. Thus is afforded a means of determining, with the utmost accuracy, every change in the weather, and by thus avoiding all the errors which arise from the carelessness or inaptitude of assistants, we may expect to arrive more satisfactorily at some important facts in climatology beyond those which we already possess. It is interesting to watch the little pencils moving to and fro marking their zig-zag or curved tracts upon the paper, and to observe the peculiar association of one phenomenon with another. The very remarkable groups of instruments which we have been describing are amongst the most striking evidences of Science in the Great Exhibition. By appliances such as these we advance our knowledge and gain power over the phenomena of nature. An instrument by which the navigator is, by a very easy method, enabled to determine the position of the centre of a storm, called by the inventor, Lieut.-Col. Lloyd, Typhodeictor, or storm-pointer, appears to be exceedingly useful. It is now fully determined that the greater storms of the tropics are revolving masses of air, moving onward at a great rate. If a ship becomes involved in one of these, she is soon disabled, but by the investigation of the law of these storms by Lieut.-Col. Reid, an easy method of determining the direction of their movement is given, and thus the mariner is enabled to sail out of their influence. It is to facilitate this that Colonel Lloyd has constructed his storm-pointer. Strange things though meet us here; we have a Storm Indicator, in which leeches crawling out of the water, as is their

habit where there is much free electricity, are made to ring bells*; and we have Count Denni's Man of Steel, composed of many thousand parts, and so contrived that from a figure of about five feet in height, it may readily be converted into one of eight. The ingenuity of these cannot be doubted; but we fear their utility is questionable. They are among the things which sometimes cause us to marvel at the variety of ways in which human invention is frequently applied without the probability of any practical result.

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* *See* MARSHALL, W. A. L.; Festival of Britain, 1951. *Met Mag, London*, 80, p. 166.

Changes in senior appointments within the Meteorological Office

The first six months of 1976 have seen an unusually high incidence of changes at Directorate level of holders of senior appointments.

On 2 January Mr N. Bradbury became Deputy Director (Forecasting) following the retirement of Mr M. H. Freeman. Dr N. E. Rider, on promotion to Deputy Chief Scientific Officer, succeeded Mr Bradbury as Deputy Director (Observational Services).

On 27 April Mr G. A. Corby, on promotion to Under Secretary, succeeded Mr J. K. Bannon as Director of Services in consequence of Mr Bannon's retirement. Mr M. J. Blackwell, on promotion to Deputy Chief Scientific Officer, succeeded Mr Corby as Deputy Director (Communications and Computing).

On 21 June Dr K. H. Stewart, on promotion to Under Secretary, succeeded Mr J. S. Sawyer as Director of Research on the occasion of Mr Sawyer's retirement, which is reported elsewhere in this issue. Mr P. Goldsmith, on promotion to Deputy Chief Scientific Officer, succeeded Dr Stewart as Deputy Director (Physical Research).

OBITUARY

It is with regret that we record the death on 17 March 1976 of Mr D. J. Mackenzie, Higher Scientific Officer, Wyton.

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked 'For Meteorological Magazine'.

The responsibility for facts and opinions expressed in the signed articles and letters published in this magazine rests with their respective authors.

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the meteorological magazine

GATE 1974 – some U.K. contributions – Part I

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THE METEOROLOGICAL MAGAZINE

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THE GARP ATLANTIC TROPICAL EXPERIMENT—AN INTRODUCTION

By B. J. MASON
(Chairman, Tropical Experiment Board)

The GARP Atlantic Tropical Experiment (GATE), designed to explore the tropical atmosphere, was successfully completed in September 1974. In what was probably the largest and most complex international scientific experiment ever undertaken, ten nations—Brazil, Canada, France, Federal Republic of Germany, German Democratic Republic, Mexico, The Netherlands, USA, UK and USSR—working in close collaboration, contributed 39 specially equipped ships, 13 large research aircraft, several meteorological satellites and some 5000 personnel to an intensive three-month study of weather systems in the tropical eastern Atlantic Ocean; in addition, more than 50 countries in Africa and South America participated by making conventional surface and upper-air observations. Despite all the technical and logistic problems, the field phase of the experiment went remarkably smoothly and, although one cannot be certain until the vast mass of data is processed and analysed, there is good reason to believe that the main scientific objectives will be largely achieved and that our knowledge and understanding of tropical weather systems will be greatly enhanced thereby. This is a tribute to three years of detailed, prescient planning and, above all, to a remarkable degree of enthusiastic co-operation between the countries that not only contributed large resources but worked amicably to achieve common objectives according to a unified operational plan.

Although the traditions for international collaboration in meteorology and geophysics were laid in the Polar Years of 1882–83 and 1932–33, the International Geophysical Year of 1957–58 and the International Year of the Quiet Sun 1964–65, GATE was quite different in character. It was not just the sum of many simultaneous national programs but a single co-ordinated experiment of unprecedented complexity, scale and intensity.

The philosophy and scientific objectives of the experiment were based on the fact that meteorological disturbances in the tropics, which behave differently in many respects from those in middle latitudes, play an important role in the circulation and energetics of the atmosphere as a whole. A better understanding of their working is essential not only for the improvement of weather forecasting in the tropics but also because, unless their influence is properly taken into account, it may not be possible to predict the weather in temperate latitudes for more than a few days ahead.

Tropical weather is dominated by showers and thunderstorms which, as satellite photographs reveal, are often organized into large clusters, 100 to 1000 km across. They are associated with the development of even larger-scale disturbances in the trade winds and play an important role in pumping heat and moisture from the tropical oceans upwards and polewards to drive the atmospheric engine.

The main task of the GATE project was to study the structure, evolution and transport properties of the various tropical weather systems and to investigate how they may interact through the transfer of energy between the different scales of motion involved. In particular it is important to discover how the transports of heat, moisture and momentum by the convective clouds, which are too small to be described by conventional observing systems and cannot be represented individually in computer models of the global atmosphere, are related to the properties of the larger-scale motions that can be measured.

The United Kingdom contributed four of the 39 ships. The hydrographic survey vessel *Hecla* executed an intensive program of meteorological and oceanographic observations and carried the Meteorological Office tethered balloon equipped with instrumental packages to measure profiles and fluxes in the atmospheric boundary-layer. The R.R.S. *Discovery* of the Institute of Oceanographic Sciences, besides carrying out its normal observational program, towed a specially designed probe to make fine-scale measurements of temperature and salinity in the upper 50 metres of the ocean. The Meteorological Office chartered two small ships to make upper-air soundings of wind using the NAVAID system to determine the wind.

The Hercules flying laboratory of the Meteorological Research Flight, equipped with radar, an inertial platform, Doppler wind-finding equipment, radiometers, and particle-samplers, was probably the most effective aircraft in the whole exercise. It flew 40 missions totalling 386 hours and recorded some 10^9 digital words of data.

During the field phase of the experiment, the Meteorological Office carried out real-time forecasts every 12 hours using an 11-level numerical model developed very quickly for the purpose and the observations gathered in the GATE area that arrived at Bracknell over the Global Telecommunication System. Experience gained then and also with the greater quantities of data that arrived later indicates that, given adequate observations, the forecasting of synoptic-scale developments in the tropics is unlikely to be more difficult than in middle latitudes.

With the field phase of the experiment successfully accomplished, we now face the daunting and most important task of processing and analysing the vast quantity of data collected. Responsibility for reduction of the observations acquired on national platforms—ships, aircraft, satellites, etc.—lies primarily with the nations themselves but, because of the different systems and instruments employed, these will have to be compared and made consistent using the results of the intercomparison and calibration trials made during the experiment. These tasks of co-ordination and integration will be carried out at five centres, each being responsible for a particular subprogram. Thus all the basic surface and upper-air observations from the GATE ships and African and South American countries in the GATE area will be processed at Bracknell and produced in the form of data sets on magnetic tape. Similarly the USA, USSR, France and Germany will be responsible for other parts of the program.

Co-ordination between the five centres and monitoring of the whole program is being carried out by a small group of scientists located in the WMO Secretariat in Geneva. Their task will end in two years' time with the deposition of the final data sets in the World Data Centres in Washington and Moscow where they will be available on demand to scientists throughout the world.

The international meteorological community will then have an unprecedented opportunity to improve our knowledge of the structure and development of tropical weather systems and to understand the interaction between the various physical and dynamical processes and between the different scales of motion. It will then be in a much better position to assess the role of tropical disturbances in the energetics of the global circulation and to incorporate more realistic representations of them into computer models for the prediction of weather and climate.

It is also intended to document the unique experience gained in, and the lessons learned from, the planning and excecution of such a large and complex experiment for the benefit of the First GARP Global Experiment and other major projects in the future.

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GATE—THE FIELD PROJECT IN 1974

By D. E. PARKER

SUMMARY

An account is given of the conduct of the 1974 GARP Atlantic Tropical Experiment (GATE). The planning procedures and scientific aims of the experiment are described. The observational network implemented for GATE, including ships, aircraft, satellites, and land stations is also described and indications are given of the performance of this network, of the particular difficulties encountered, and of the progress of the resulting work in the GATE data-processing centres.

1. INTRODUCTION

This paper gives a general description of the GARP Atlantic Tropical Experiment (GATE), as a background for the following articles on particular United Kingdom contributions. The description here will be brief; fuller details can be found in GATE Reports Nos. 15 to 19.

2. PLANNING AND INTERNATIONAL CO-OPERATION

It has long been realized that meteorological disturbances in the tropics are important in the general circulation of the atmosphere. Improved knowledge and understanding of tropical meteorology is vital for the success of forecasting not only locally but also, at least for forecasts for more than two or three days ahead, in middle and high latitudes. This was one of the major factors which led to international discussions on and proposals for a tropical meteorological experiment.

Note. Certain words and expressions which may not be familiar to some readers are explained in the 'short glossary' on pages 244–245.

Initially the Joint Organizing Committee (JOC) of the Global Atmospheric Research Program (GARP) proposed that the experiment be held in the tropical North Pacific; but logistic considerations led to a decision to carry out the experiment in the tropical North Atlantic. Subsequently, satellite cloud photographs showed that large cloud clusters, which are generally manifestations of tropical disturbances of similar or larger scale, were most abundant in the eastern tropical North Atlantic which was therefore chosen as the location of the experiment. It was decided, however, not to have the experiment too near the African mainland because one aim was to study the disturbances and clusters away from the influence of land and topography.

Once the basic aims had been formulated by the JOC (see Section 3 below), the major tasks of completing the details and designing a practicable experiment were allotted to an International Scientific and Management Group (ISMG) formed for the purpose. The ISMG was located in Bracknell where it had access to excellent facilities (e.g. the National Meteorological Library) but there was also very close liaison between the ISMG and the WMO which with ICSU (International Council of Scientific Unions) (mainly Universities and non-governmental scientific organizations) is joint patron of GARP.

The operation's base for GATE was chosen to be Dakar, Senegal, where excellent harbour, airport and general technical and accommodation facilities are available.

3. Aims

Meteorological observations in the tropics, especially in the upper air and over the oceans, have nearly always been sparse. Before GATE they had none the less demonstrated that tropical disturbances and cloud formations occur on many scales. These scales encompass the mean Hadley north–south circulation, monsoon flows, and various east–west circulations (global-scale); tropical waves and monsoon cloud-clusters (1000 to 5000 km: A-scale); cloud clusters and tropical storms and hurricanes (100 to 1000 km: B-scale); cumulonimbus groups and lines and other mesoscale effects (10 to 100 km: C-scale); and phenomena on the 1 to 10 km or D-scale such as individual large clouds and thunderstorms and downdraughts. What GATE set out to elucidate was how the motions on one scale influence those on another, and what were the mechanisms by which tropical motions affected higher latitudes. The relationship between A and B scales is particularly significant, and A–B interaction was therefore the central interest of the experiment.

A single numerical model cannot deal with motions on all scales from A to D explicitly. It is therefore necessary to 'parameterize' the smallest scales in terms of the larger, whose structure is defined by the variables of the model. It was a prime object of GATE to provide data that would enable the formulation and testing of parameterization of motions on scales below about 100 km.

A further aim of GATE was to obtain data over a large area from eastern Africa to western South America in sufficient quantity and of adequate quality to provide numerical models with a good basis for making and checking experimental forecasts involving the tropics.

To see the central aim in less abstract terms, consider for example 700-mb easterlies over West Africa and the Atlantic with easterly-wave troughs over Nigeria (5°E) and off the west coast (20°W). Suppose that an area of strong

convection of dimension 200 km ('convective cloud cluster') exists near the western trough (i.e. near the concentrated part of the GATE ship network (Figure 1)). Then we would very much like to know:

To what degree will the convective cloud cluster weaken the trough or strengthen it?
Will the cluster aid the normal westward movement of such a trough?
To what extent will the horizontal flow and vertical motion and large-scale advection (if any) associated with the trough help to strengthen or weaken the cluster, or move it?
How will the large-scale temperature and moisture fields change?

Cloud clusters themselves are made up of large numbers of individual cumulonimbus cells, which are often observed to form coherent C-scale groups. The extent and intensity of the cluster is therefore probably not wholly dependent on the large-scale flow but is influenced by C-scale features. In other words, B–C interactions may be important and C-scale phenomena may thereby have an important influence on motions on the largest scales. It is hoped that the GATE data will clarify this.

We should also like to know how the boundary-layer influences the cluster. It may be for example by a positive feedback involving boundary-layer convergence, vorticity and moisture content on one hand and cluster development on the other (Conditional Instability of the Second Kind or 'CISK').

The influence of the ocean on the cluster is likely to be important: clusters appear to undergo changes when they cross coastlines, and areas of warmer water favour their development.

The Intertropical Convergence Zone (ITCZ) is a region where cloud clusters are numerous. The intensity of the convergence will affect any cluster in the zone.

The cluster transports heat upwards and the flow in the upper troposphere transports this heat polewards. It would be valuable to know what are the exact mechanisms involved and whether the interaction between the cluster and the upper tropospheric flow enhances or inhibits the process.

For practical reasons the planning of GATE was divided into five parts: synoptic-scale, convection, boundary-layer, radiation and oceanography. Each of these formed a 'subprogram' of GATE. The subdivision was made to facilitate planning (suitable persons could more easily be found if only a small scientific area were to be covered by their work) and to facilitate data management. The subprograms each elaborated the basic aims of GATE in their own terms and added subsidiary subprogram objectives.

4. Experimental design and implementation

For GATE a network of 'B' (and 'C') ships at not more than 150-km spacing (for B- and C-scale data) in the eastern Atlantic 'B-scale area' needed to be surrounded in the immediate vicinity by 'A/B' ships less than 500 km apart (for B-scale and synoptic-scale data) and in remoter areas by 'A' ships 500 to 1000 km apart (for synoptic-scale data). Special aircraft were needed to supply additional detail to the measurements within the concentrated network of ships. Satellites were vital if a complete picture was to be obtained, and so were the shipboard boundary-layer and oceanographic measuring systems, especially in the B-scale area. Finally, the existing World Weather Watch land station

network needed to be enhanced to provide adequate synoptic-scale information.

For practical reasons the observation periods for ships and special aircraft were limited to three 21-day 'phases': 26 June to 16 July, 28 July to 17 August, and 30 August to 19 September. Land stations and satellites, however, functioned continuously for the whole 100 days of GATE (15 June to 22 September 1974). The limitation on the lengths of time of ship observations would of course be unacceptable for climatological studies, but the synoptic-scale atmospheric waves and disturbances have a typical time-scale of 4 or 5 days while the smaller-scale features are much more short-lived (lifetimes 1 day or less) so that the limitation was not serious.

Figures 1 and 2 show the ship network during Phase III. Because of problems with upper-wind measurement on some 'A' ships, modifications to plans for ship locations had been made and are indicated on the diagram. The distributions of 'A', 'A/B' and 'B' ships in Phases I and II were similar, but there were no 'C' ships. Locations of 'A/B', 'B' and 'C' ships are shown on an expanded scale in Figure 2, which also indicates which of these ships had weather radars. 'A' ships made 6-hourly upper-air soundings but 'A/B', 'B' and 'C' ships usually made 3-hourly soundings.

Figure 3 illustrates the shipboard equipment for boundary-layer measurements. Many ships also made extensive oceanographic measurements, and radiation measurements including radiometer-sonde soundings.

Thirteen aircraft out of a hoped-for fourteen took part in GATE. The USA provided nine, the USSR two, and the UK and France one each. Aircraft missions were divided into Basic GATE (B-scale area convection), Boundary Layer, Radiation and Oceanographic, with short-range missions into convective vortices near Dakar, cloud-physics missions and windfinding-dropsonde missions as additions.

The mission type was selected each day by an international 'Mission Selection Team' in Dakar, Senegal, where the aircraft were based. Their selection was based on forecast weather conditions, aircraft availability, and an approximate knowledge of the achievements of previous GATE missions so that for example hitherto deficient aspects could be remedied. The weather forecasts, which were greatly aided by frequent satellite images, achieved a high degree of success from an early stage in the experiment. They were produced by an international team in Dakar. The total number of sorties was about 290—the maximum hoped for, and there were no serious accidents.

The Basic GATE aircraft missions concentrated on B- and C-scale convective features in the B-array and sampled many C-scale features which turned out to be more numerous than B-scale ones, the incidence of which had probably been overestimated from satellite photographs because of the occurrence of large thick cirrus shields. There was a change in emphasis too in the Basic GATE missions because convective features in the B-array were found to be very transient, so that it was impossible to fly successive missions into the same feature at e.g. 12-hour intervals. Also the convection did not 'move' westwards so as to allow studies of the recovery of the atmosphere in the wake of clusters. These factors all increased the amount of mission time spent sampling C-scale convective phenomena which grew and decayed *in situ*. After their decay further convection would develop and decay *in situ* at some point further west according to the progress of the associated synoptic-scale disturbances. Because of the short lifetime of systems, detailed mission planning

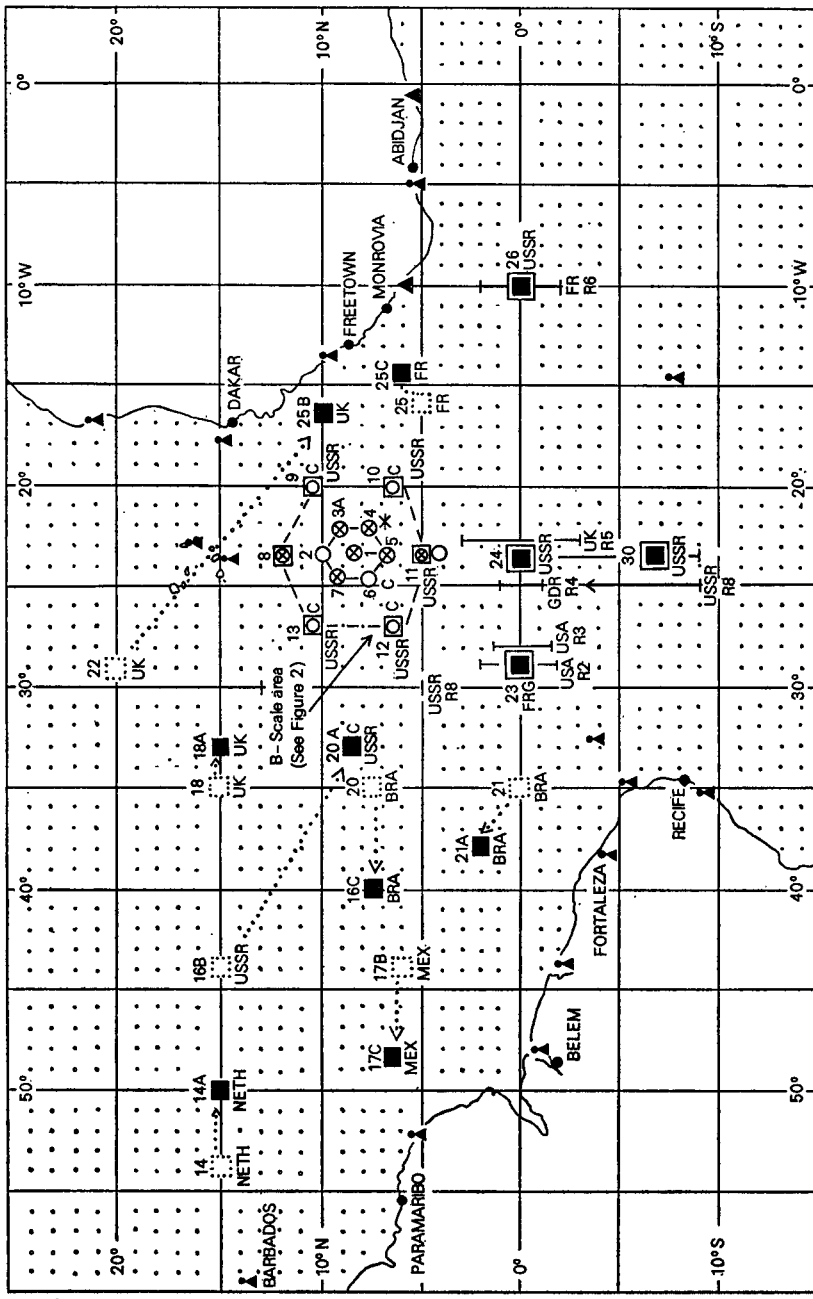
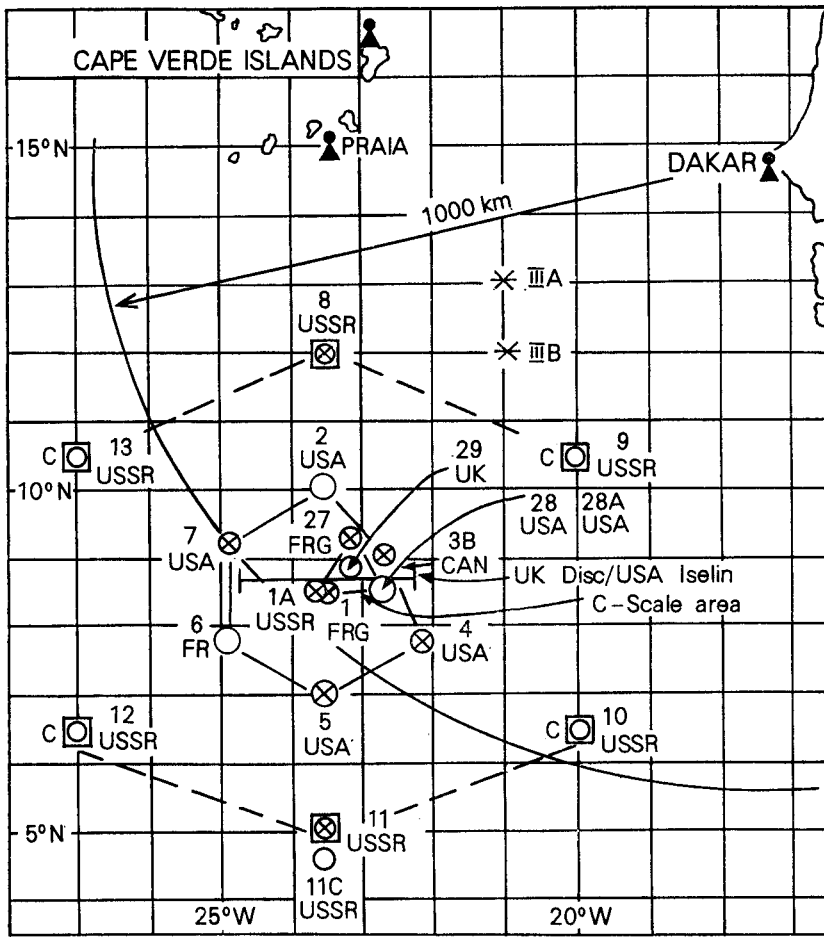


FIGURE 1—SHIP DISTRIBUTIONS, PHASE II (28 JULY–16 AUGUST 1974)
See Figure 2 for definition of symbols used to designate types of ship's positions.

PHASE III (30 Aug–19 Sept 1974)



KEY

- ⊗ B-Scale radar ship-position
- ○ B-Scale ship-position
- ◻ A/B-Scale ship-position
- ■ A-Scale ship-position (Actual)
- ▲ Land station Radiowind/Radiosonde
- ▲ Land station Radiowind only
- ■ A-Scale ship-position (Planned & actual)
- ⊗ A/B-Scale radar ship-position
- C Communications ship
- ⋮ A-Scale ship-position (Planned)
- ⟷ Roving oceanographic ship
- ✳ Intercomparison Point

FIGURE 2—SHIP DISTRIBUTIONS FOR THE B-SCALE AREA

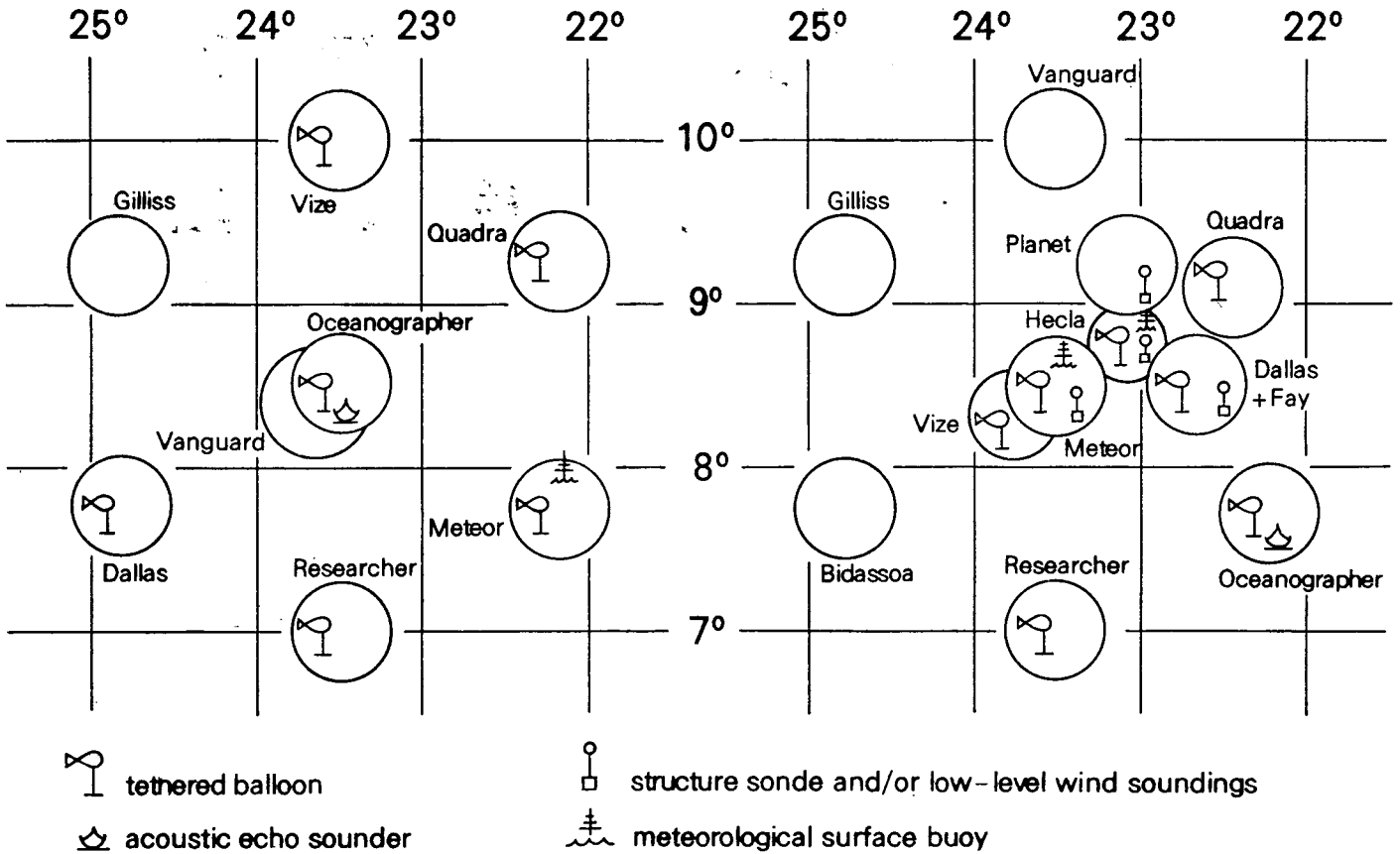


FIGURE 3—SHIP POSITIONS OF THE INNER B-SCALE HEXAGON AND SPECIAL BOUNDARY-LAYER EQUIPMENT
Left: Phase I and Phase II. Right: Phase III (*Vanguard* and *Vize* exchanged positions before Phase II).

had to be carried out by the Airborne Mission Scientist on arrival in the B-area. However, the basic type of mission could be planned beforehand because it was possible in general to give a successful 24-hour forecast of B-area weather type.

For the Boundary Layer missions, the Mission Selection Team introduced a new type of mission involving repeated short north–south transits of the ITCZ, in addition to the original type of ITCZ mission which involved a single long north–south transit reaching near to the equator. Most Boundary Layer missions, however, concentrated not on the ITCZ as such but on B- and C-scale convective features or on fair weather areas in the B-area.

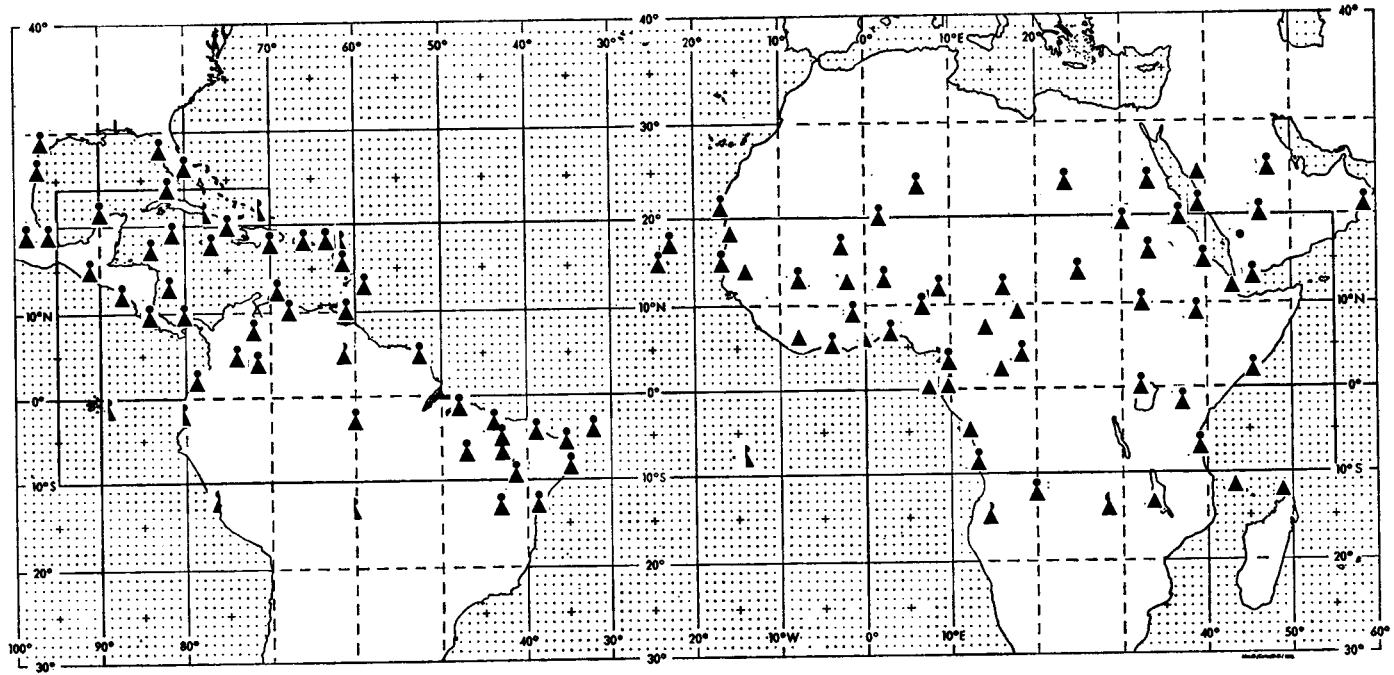
A few missions into convective vortices and squall lines near Dakar were flown by the short-range aircraft. For safety reasons the most active parts of squall lines had to be avoided, but interesting data are expected.

The windfinding-dropsonde aircraft played a vital part in filling in gaps in the A-scale ship network east, north, and north-west of the B-array, and in monitoring synoptic-scale disturbances and their associated convection as these progressed westwards from the B-array or from the Cape Verde Islands area.

After considerable apprehension due to delays in launching, the USA geostationary satellite SMS-1 began successful transmission in the visible (½-n.-mile resolution) and infra-red (4-n.-mile resolution) in time for the first day of Phase I, and continued to function excellently throughout GATE (see Plate IV). The subsatellite point at 0°N, 45°W was 15° further west than planned, but this did not affect operations over the Atlantic. Images were normally available at ½-hourly intervals, though on a few special days in Phase III 15-minute imaging was carried out. Visible images with resolutions of ½ and 2 n. mile were generally produced, the former covering the B-area and environs and the latter covering the GATE area from about 0° to 50°W. These images were available in Dakar and also archived in the USA. In addition ½-n.-mile resolution visible images covering the whole earth-view disc, which included all the GATE area west of 15°E, have been archived in the USA. Infra-red images at 4-n.-mile resolution covering the whole disc were also available in Dakar and archived in the USA.

The SMS-1 images not only aided forecasting and detailed mission planning, but are an enormous reservoir of data for studies of convection, radiation, and synoptic-scale meteorology. Sequences of SMS-1 images were made into movie loops in Dakar, so that wind patterns could be estimated, thus aiding operational planning, and winds were also derived and archived in the USA. These latter winds were mainly for low and high levels and were on the synoptic scale, and were transmitted globally for use in forecasts and real-time numerical models, but there have since GATE been derived some subsynoptic-scale winds for low, medium and high levels over the B-area.

The GATE data coverage would have been far from complete without the surface, pilot-balloon and particularly radiowind and radiosonde data from World Weather Watch land stations. The functioning radiowind and radiosonde land stations are shown in Figure 4 which also depicts the GATE area boundary. In addition several equatorial land stations round the globe outside the GATE area provided radiowind and radiosonde data for studies of global-scale equatorial waves.



Key: 00 GMT radiowind
12 GMT radiowind
00 GMT radiosonde
12 GMT radiosonde

FIGURE 4—LAND RADIOWIND AND RADIOSONDE STATIONS WHICH ARE KNOWN TO HAVE FUNCTIONED DURING GATE

5. Major problems encountered

During the field operations two major problems were encountered: firstly, there were serious difficulties in operating shipboard upper-air windfinding systems based on navigational-aid 'Omega' or 'very-low frequency (VLF)' signals, and secondly, little or no upper-air data arrived from a substantial number of important land stations scheduled to measure upper winds. There were other problems too, such as difficulties in co-ordinating low-flying aircraft with tethered balloons, but these problems were generally solved satisfactorily, and although we cannot yet be completely certain that data from apparently perfectly operating systems will turn out to be satisfactory, we can state that apart from the above two major problems GATE proceeded very smoothly and is expected to have produced plentiful high-quality data.

(a) *Omega and VLF upper-air windfinding*

Omega and VLF windfinding are both based on the following principle. Signals of very long wavelength from three widely separated source stations are received by the sonde. From the relative phases of the signals, the sonde location is determined. Repeated locations are used to derive sonde velocity.

It was found that the signals were often rather weak and noisy, especially (as expected) in the south of the ship area. Also some ships had software and hardware problems with their signal processors. However, where even weak signals were obtained, the possibility exists of recovering the wind data by means of a complex computer program if the signals were recorded magnetically, or manually from strip-charts.

Because of the Omega and VLF windfinding problems the planned 'A'-ship positions in Phases II and III were modified so as to have ships providing reliable upper-wind data on the synoptic scale immediately outside the 'A/B' ship network (in which only radar windfinding was used).

(b) *Upper-air data from land stations*

One of the changes in an 'A'-ship position, that to position 25B at 10°N, 16½°W (Figure 1) was mainly the result not of ship upper-air windfinding difficulties but of the absence of two vital coastal land stations which should have provided upper-wind data. The absence of these two stations did not constitute the whole problem, however, and during the field phase it was found that only 36 per cent of planned radiowind and radiosonde messages were received at Bracknell within nine hours of observing time. It had been suspected that poor communications would cause many data to be lost and therefore a mail collection of teleprinter paper tapes had been arranged (Jarvis (1976) and Spackman (1976) in this issue of the *Meteorological Magazine*). This collection was very successful.

6. Data handling

Data from ships, buoys, aircraft, and satellites specifically devoted to GATE were collected by the National Processing Centres (NPCs) of the nations operating the platforms. At the NPCs preliminary quality controls ('national validation') are being carried out, with the aid of data from the special intercomparison measurements made on board their own ships and aircraft during the experiment. Where necessary Omega and VLF upper-air data are being

reprocessed. Also at the NPCs the data are being sorted and put into agreed formats on agreed computer-compatible media.

The Subprogram Data Centres (SDCs) will further control the quality of the data ('international validation') using if necessary the special intercomparison data from as many platforms as needed. After final formatting the data will be sent to the World Data Centres (WDCs) A and B, at some time between late 1976 and the end of March 1977.

In addition the Synoptic-Scale Subprogram Data Centre (SSDC) at Bracknell will format and control the quality of the GATE land station data received there and send them to WDCs A and B as internationally validated data by late 1976 or early 1977.

7. Conclusion

It appears that despite the problems described in Section 5, GATE has met with substantial success. It now remains for us to complete the data management and to use the data to improve our understanding of the tropical atmosphere. Interested readers can find preliminary scientific results presented already in GATE Report No. 14. But for those who wish to know first the details of the specific UK contributions to GATE, the following papers in this present issue will supply them with at least some of the information they need.

551.506.24

GATE—THE SYNOPTIC-SCALE SUBPROGRAM DATA CENTRE

By E. A. SPACKMAN

Summary

The paper describes the work of the Synoptic-scale Subprogram Data Centre, which is dedicated to preparing data sets of synoptic-scale observations made during GATE. The data sets, most of which will be processable by simple computer programs, will be supplied to GATE Archives for the use of scientists carrying out research on the tropical atmosphere. The purpose of the Data Centre, its data sources, products and progress up to March 1976 are briefly indicated.

Introduction

The Synoptic-scale Subprogram of GATE is one of five subprograms which make up the scientific content of GATE. It is principally concerned with the large-scale features of the atmosphere in the GATE A-scale region covering the tropics from west of Panama to the Seychelles. Basic information and guidance is given in GATE Report No. 6 (The Synoptic-scale Subprogramme for the GARP Atlantic Tropical Experiment) which is also an historical record of the planning phase. The main aims of the subprogram may be summarized as follows:

1. To describe the synoptic-scale disturbances in the tropical atmosphere from eastern South America to West Africa.
2. To describe the average state of the troposphere over the GATE area.
3. To describe the synoptic-scale environment of cloud clusters passing through the B-scale area (centred on 8½°N, 23½°W) in sufficient detail to allow investigations to be made of the interactions between the clusters and larger-scale motions.
4. To create complete and internally consistent data sets for tropical numerical prediction models.

In order to achieve these aims, observations are being collected by the Synoptic-scale Subprogram Data Centre (SSDC) from many sources and assembled into data sets. The work is being carried out by a small group within the Dynamical Climatology Branch. Supporting work which involves processing a large amount of paper tape in telecommunication format is being undertaken by the Data Processing Branch.

The Data Centre Plan is given in GATE Report No. 13, Part III, Section 5, and more recent additional information on the contents of the data sets can be found in GATE Report No. 16, Section 5.6.

The SSDC has already sent two data sets (a Quick Look Data Set and an Unvalidated Teleprinter Tape Data Set) to GATE Archives (World Data Centre-A in Asheville, USA and World Data Centre-B in Moscow, USSR). Three other Data Sets are being produced—an Intercomparison Data Set, a Final Validated Data Set and a SPECI Data Set. They are expected to be ready by the end of 1976. Each data set will conform to the format prescribed for the international exchange of GATE data in GATE Report No. 13, and will have comprehensive written documentation. Layouts for each type of observation (upper-air sounding, surface, upper-air single-level etc.) that allow all reported values and quality-control information to be stored in a reasonably compact fashion have been developed by the SSDC. It is believed that there are no other suitable character formats in international use at the present time.

Observations

Most type of observation used in synoptic studies of the atmosphere are being collected. During GATE the usual surface (SYNOP, SHIP and SHRED), upper-air (TEMP, TEMP SHIP, PILOT and PILOT SHIP), aircraft (AIREP) and satellite (SIRS and GOES) observations were made and transmitted over the Global Telecommunication System (GTS). Many radiosonde stations (particularly in West Africa) augmented their schedules and made two ascents a day whilst three stations (Praia in the Cape Verde Islands, Dakar and Bamako) usually made four ascents a day. In addition to the above, automated in-flight recordings were made by some specially equipped commercial aircraft, and 'dropsonde' soundings were made by some GATE aircraft.

Sources of data

Observations are being collected from three principal sources:

(a) Bracknell Regional Telecommunication Hub (RTH), which received data in near real time.
(b) Selected Meteorological Centres, which sent paper tapes in telecommunication format by mail to Bracknell.
(c) GATE National Processing Centres (NPCs) which are processing the observations made from the GATE platforms (ships and aircraft).

Paper tapes in telecommunication format from the Bracknell RTH and selected Meteorological Centres are being processed through the Synoptic Data Bank stored in the United Kingdom Meteorological Office COSMOS Computing System by the use of methods developed for operational forecasting purposes. The reports are retrieved from the Bank by means of standard Meteorological Office routines and are rearranged before storage in the Data Centre data sets. For upper-air soundings, the various parts of a report (in near real time they

To face page 234

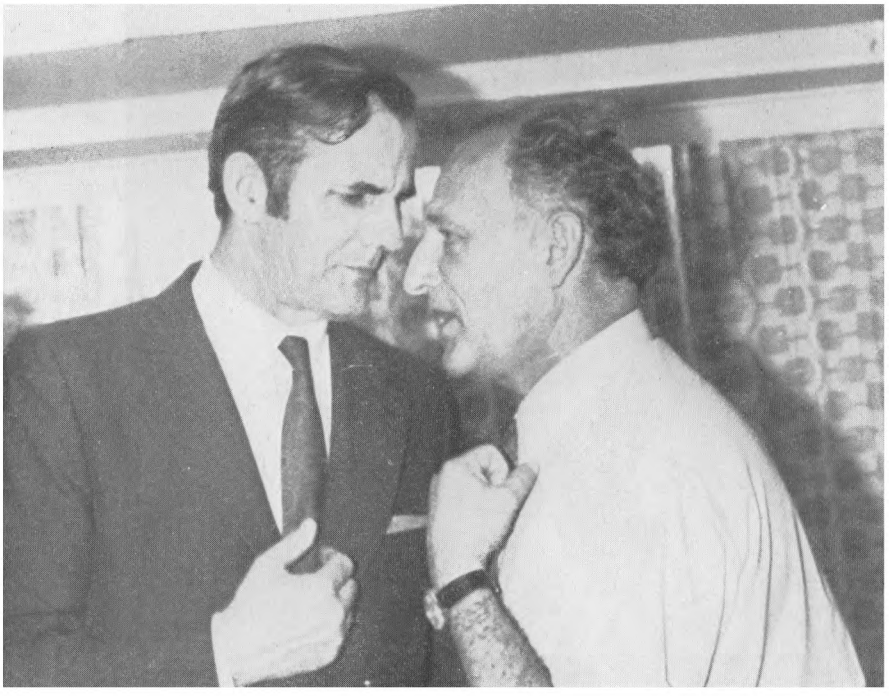


PLATE I—DR B. J. MASON, CHAIRMAN, TROPICAL EXPERIMENT BOARD, AND PROFESSOR M. A. PETROSYANTS, CHIEF SCIENTIST OF THE SOVIET GATE EXPEDITION AT A PARTY ON BOARD THE USSR RESEARCH SHIP *Professor Zubov* IN DAKAR, 25 JULY 1974

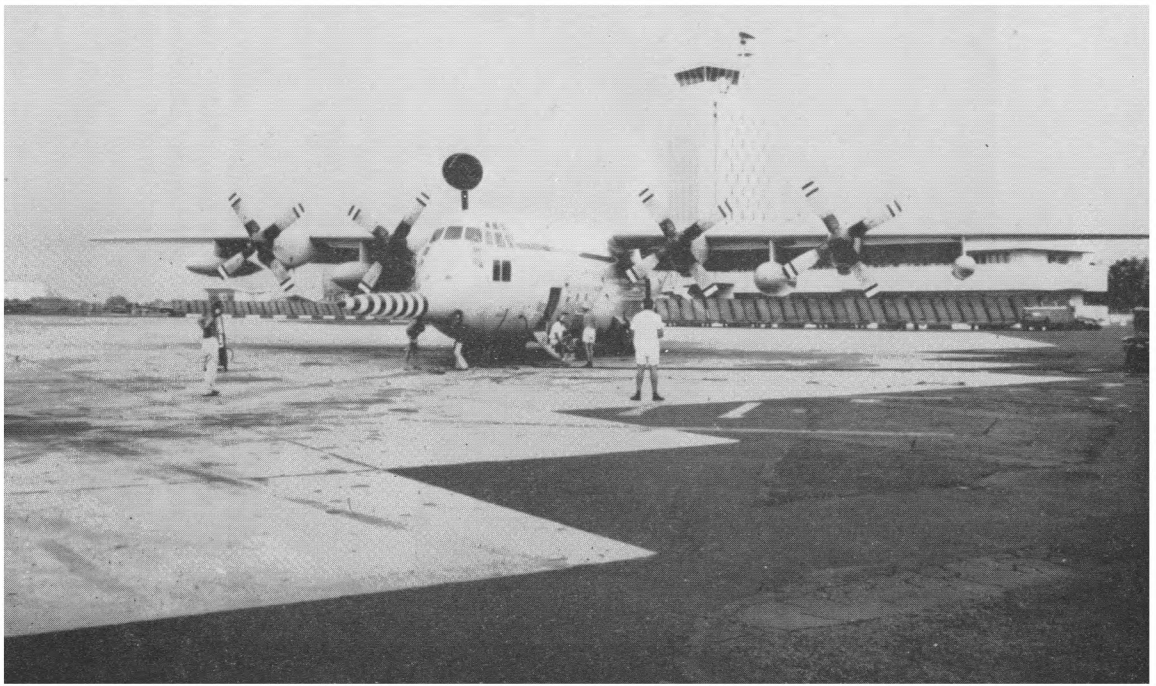


PLATE II—FINAL PREPARATIONS, AT DAKAR AIRPORT, BEFORE DEPARTING ON A 9-HOUR GATE MISSION

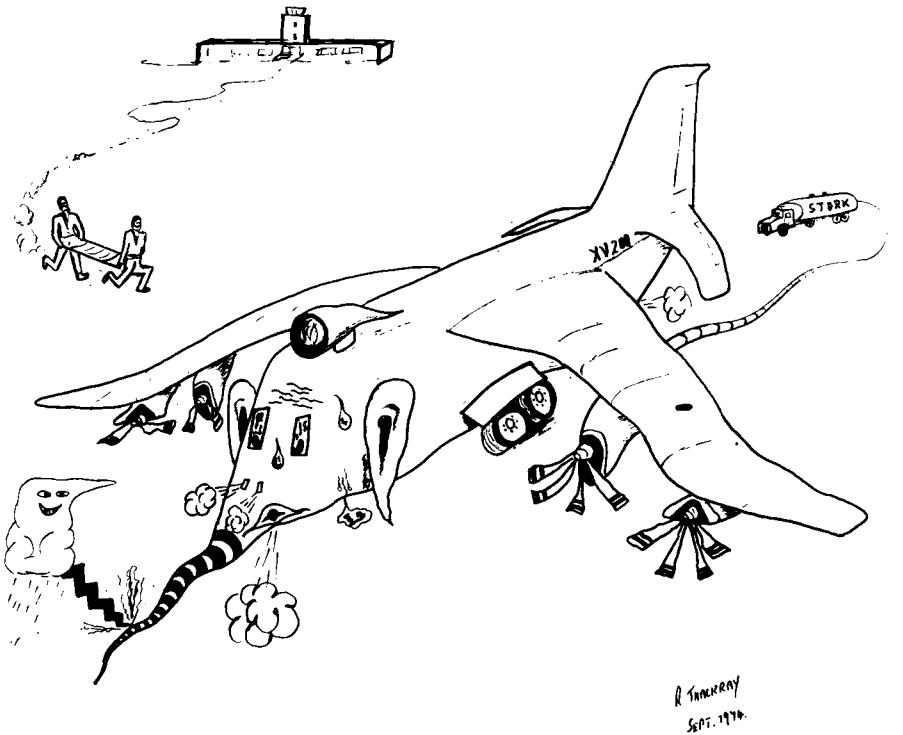


PLATE III—'AFTER 3 MONTHS IN THE TROPICS WE WERE ALL A LITTLE TIRED'

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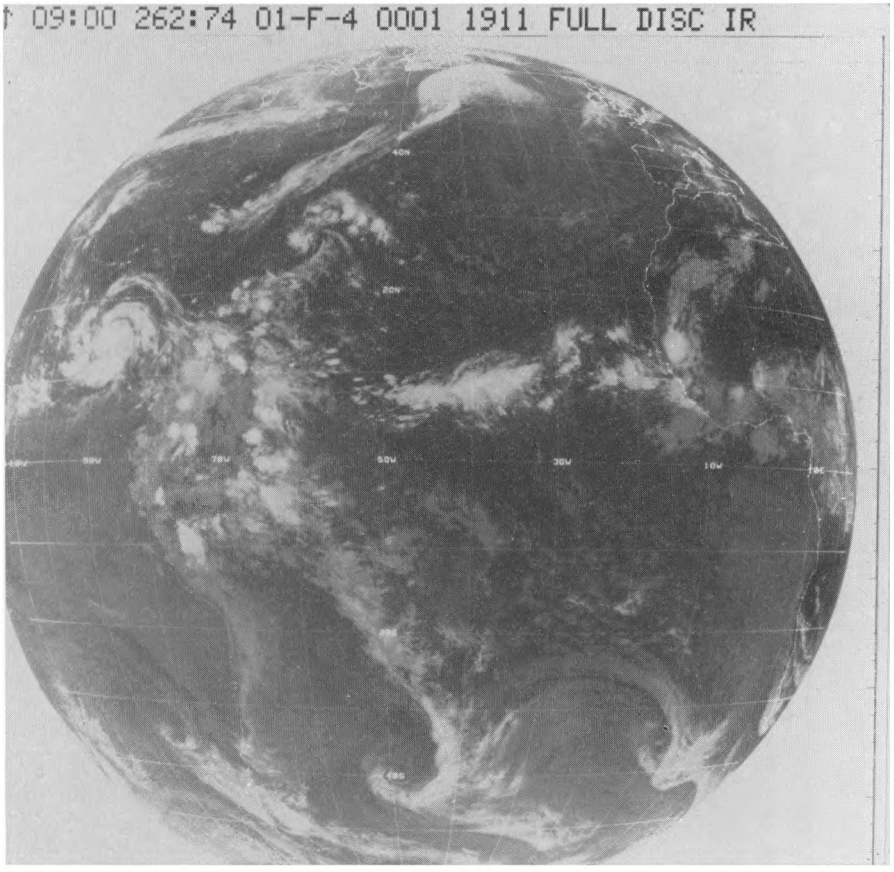

PLATE IV—INFRA-RED IMAGE OBTAINED FROM GEOSTATIONARY SATELLITE SMS-1 AT 0900 GMT ON 19 SEPTEMBER 1974

Cloud from a well-developed ITCZ is visible at about 10°N over the Atlantic. Hurricane Fifi can be seen at about 15°N, 85°W. See page 230.

are received in up to eight separate sections) are combined together into one report with levels in order of decreasing pressure. NPC data for the GATE platforms are being received on magnetic tape in GATE format and will have been nationally validated.

Additional observations are being collected in other ways. Some have been received in manuscript (e.g. from Angola and Cuba), some are being obtained from regular or special publications (e.g. from Cameroun) and some are already available within the Meteorological Office on punched cards (e.g. from some stations in the Sudan and East Africa). Surface observations from merchant ships, which were collected in the Federal Republic of Germany, have been received on magnetic tape in GATE format in the International Marine Meteorological Punched Card format. Commercial aircraft reports, collected by three groups in the USA have been received on magnetic tape; they consist of standard in-flight reports (AIREPs), special reports handed in at airfields and automated in-flight reports. Commercial aircraft reports have also been received from a Brazilian collection. Satellite winds have been received from the USA which make a more complete set of data than was available over the GTS.

Validation

As well as creating the data sets the Data Centre has a responsibility to validate the observations. There are two aspects of this work—'format validation' and 'quality control'.

Format validation involves checking the layout of the input data, recognizing errors and, where possible, correcting them. This is done automatically as reports are recognized and stored in the Synoptic Data Bank and subsequently as they are retrieved from the Bank and decoded. NPC data, which will have been nationally validated by the country supplying them, should not contain format inconsistencies. However, if minor inconsistencies are found they will be corrected as the reports are converted into SSDC formats. More serious errors will be referred back to the appropriate NPC for corrections. Format validation also involves checking that the output of the Data Centre itself is consistently correct. This will be achieved by using the product for scientific investigations at the Centre and within the Meteorological Office (e.g. by the Tropical Group of the Dynamical Climatology Branch).

Quality control involves checking the meteorological content of each parameter. Observations in the Quick Look Data Set were only subjected to the normal checks of the Synoptic Data Bank routines, but more elaborate tests have been devised and programmed for the Final Data Set. Each parameter will be tested, where possible, and if appropriate, against climatological limits, for internal consistency within each report, for acceptable rate of change with time, for permissible value of a coded parameter and so on. Many of the tests are based on those already performed by the Synoptic Data Bank (but made appropriate to the tropics) and those in use by other meteorological services. Most reported parameters have a quality-control indicator to indicate the quality of the observation and the type of test failed (if any). Data will not be destroyed unless they are meaningless and a method based on the probable cause of the error exists for creating a better value.

The SSDC is studying the climatology of the GATE area for 1974 in terms of the means for each Phase of GATE. This is to aid the Centre in its validation exercises and it is expected that charts of temperature, height and wind will

be produced for selected levels in the atmosphere for the whole of the GATE A-scale region. From these charts the Centre will establish 'climatological' limits for GATE observations, attempt to reconcile differences between instruments (particularly those measuring upper-air temperature) and verify results obtained from studies of the special intercomparison observations.

THE DATA SETS

1. *The Quick Look Data Set*

The Quick Look Data Set (QLDS) contains all the synoptic reports received in near real time in a recognizable form through the Bracknell RTH, and for Phase I only, observations recovered from the paper-tape data collected by mail. The data set contains data for the period from 1 June 1974 to 30 September 1974 inclusive although particular attention is being given to those observations made during the three main phases of GATE. The area covered by the data set is 95°W to 55°E and 10°S to 25°N. A few upper-air stations, Atuona, Gan, Ponape and Singapore, which are very near to the equator but outside the area, are also included so that the equatorial stratospheric circulation can be studied.

2. *The Unvalidated Teleprinter Tape Data Set*

This data set (which has also been called the Quick Look Data Set—Supplementary) contains the paper-tape information in telecommunication form collected by mail during 1974. It is a direct copy on magnetic tape of the paper tapes and is intended to provide scientists with data much earlier than they would otherwise be available. Reports, which have not been validated or properly ordered, are reproduced as received in WMO codes and other miscellaneous codes and plain language and contain distortions and errors which characteristically occur with near-real-time data. Although it is relatively easy to print out the data set and use the information manually (e.g. for plotting synoptic charts) it will be extremely difficult to process automatically by computer unless the user has software with which to decode messages in WMO code. The data set is contained on five magnetic tapes and was sent to GATE Archives early in 1975.

3. *The Final Data Set*

This will contain reports for the same period as the QLDS but the area is extended from 10°S to 15°S, so that a few more upper-air reports will be available in South America and Africa (where data are otherwise sparse), and from 55°E to 60°E. It is planned that all observations will be comprehensively validated and doubtful values flagged. The purpose of this data set—the main product of the Data Centre—is to attempt to provide a complete and internally consistent set of observations which can be used in the development of tropical numerical prediction models and for synoptic studies of the tropical atmosphere. However, since most of the land data will have been collected in telecommunication codes—either on paper tapes mailed to Bracknell or over the Global Telecommunication System—it is inevitable that some observations will have been lost while others will have been corrupted to the point at which they cannot be recognized or used. It has not been possible to get back-up information on paper tape from all countries, particularly some with internal political

or economic difficulties, and this causes a further loss of data. At present (March 1976) the indications are that recovery of observations for land stations will be good and that serious deficiencies will only occur in those areas where there were no observing stations—for the upper air this includes parts of central South America, Liberia, Sierra Leone, Guinea, northern areas of Mauretania and Mali and parts of central Africa. Coverage of the Atlantic Ocean, which will depend on the numbers of observations supplied by the NPCs, is expected to be good except to the west of the B-scale region where there will be less data than envisaged in GATE plans, near the northern boundary and south of the Gulf of Guinea. Also there are no upper-air observations in the GATE area of the Indian Ocean. It is expected that there will be about 25 per cent more data overall than there were in the QLDS, but the improvement will vary considerably from station to station and from observation hour to observation hour. Surface-data coverage will be considerably improved in South America (few observations were received in near real time), in Africa (there will be more reports at 03, 09, 15 and 21 GMT) and for GATE ships (hourly observations should be available). The biggest improvement in upper-air reports will be in western South America (a good supply of observations will be available for several stations which were rarely or never received over the Global Telecommunication System at Bracknell) and eastern Africa. There should also be reports at three-hourly intervals from some ships in the B-scale and A/B-scale regions—particularly in Phase III.

4. *The Intercomparison Data Set*

This will contain synoptic-type observations made by the GATE ships (and possibly GATE aircraft) during the formal intercomparison periods. The purpose is to provide the data in such a form that instrumental differences can be evaluated. The information may also be used to create or justify adjustments to the main body of observed data before its use. Most A-scale intercomparisons took place just before Phase I or just after Phase III. With upper-air intercomparisons the 'in-train' method of flying two radiosondes on one balloon was usually employed while the windfinding equipment tracked the same balloon. Surface intercomparison observations were made aboard adjacent ships or on board a ship while alongside a buoy which was automatically recording the same parameters.

5. *The SPECI Data Set*

A data set is to be created from the SPECI reports received on the paper tapes from Meteorological Centres. They contain information on the time of occurrence of certain phenomena, for example, the onset of rain, thunderstorms, strong winds etc. These can be useful in some synoptic studies or investigations such as the study of squall lines.

551.506.24:681.3

COMPUTER PROCESSING OF GATE TELECOMMUNICATION DATA

By C. H. JARVIS
(Meteorological Office, London/Heathrow Airport)

SUMMARY

The method of processing telecommunication data for GATE is described. The advantages of sending telecommunication paper tapes by post are assessed. The uses to which the processed data have been put are briefly mentioned.

INTRODUCTION

The responsibility for processing meteorological telecommunication data for GATE was undertaken by the Meteorological Office. The Data Processing Branch (DPB) already had considerable experience in the presentation of telecommunication data both for use in objective-analysis schemes and for archival storage. It was decided that the DPB Operational Synoptic Data Bank (SDB) could accommodate the additional data with trivial modification. Furthermore, only minimal computer-programming effort would be necessary to recognize and store the additional code types and message formats proposed for GATE. Paper tapes received through the normal postal system would be acceptable for computer processing even some weeks after the date-time of their report. The techniques used to test improvements in the SDB suite of programs were also capable of handling such late-arriving data.

Once the data were stored, the comprehensive library of retrieval routines already available to SDB users could supply the variety of GATE demands—primarily for telecommunication monitoring, computer modelling, and the GATE archival data set.

REAL-TIME DATA SOURCES

The routine telecommunication tapes provided for the SDB by the Telecommunications Branch already contained a substantial proportion of data for the GATE area. The Global Telecommunication System (GTS) was augmented by special bulletins from within the GATE area for stations and hours not normally transmitted, and for surface and upper-air reports from the participating GATE ships; use was also made of radio-teleprinter broadcasts from Nairobi, Nicosia, Offenbach, and Moscow, the last having a special direct link from a Russian ship in the area. The additional African observations were received regularly, but the South American contribution in real time was limited.

The Telecommunications Branch, on their own initiative, found that the interception of the Paris–Dakar point-to-point radio-teleprinter broadcast was possible at Bracknell. Within six hours of making this discovery in early August the SDB was processing the first Dakar observations. The Dakar broadcast continued to provide a valuable back-up to the GTS throughout the rest of GATE. A close informal liaison with the Telecommunications and Dynamic Climatology branches continued throughout the experiment. Thus improvements to the joint plans were quickly implemented.

POSTAL DATA SOURCES

Before the experiment began it was recognized that a significant number of observations would not be available from the GTS. Many of these observations

were for the areas where data were sparse, which made it important wherever possible to collect them subsequently. Furthermore, the teleprinter data received at Bracknell are not sufficiently error-free for them to be the only source for GATE use. Radio-teleprinter reception is particularly variable in quality. A back-up was required. A 5-hole paper tape is usually produced by transmitting centres, coincident with their sending of reports. It was suggested that these tapes should be sent to Bracknell by mail. Most national and regional centres already cut these tapes, so very little extra work would be required. Furthermore since the messages are in international codes (and any 'national practices' are listed in WMO publications), the differing archiving conventions adopted by participating countries were not relevant. Some centres produced 5-hole paper tapes specially for this purpose, and three centres produced manuscript data (unfortunately in three different formats). Tedious clerical effort was required in each case to convert the data received to a suitable computer-input standard. This indicates how difficult the whole problem could have proved.

Participation was encouraged by providing each collecting centre with cartons for each day's tapes and addressed postal boxes for weekly despatch to the DPB. Some 8000 such cartons were labelled and sent out by the DPB staff during April 1974.

Problems were few, although one parcel of empty boxes languished in an overseas customs shed for the whole GATE period. The boxes were returned by a variety of methods despite instructions to senders to use only air and sea postal services. Airline captains personally handed some boxes to the Meteorological Office at Heathrow, others came by air freight. The last box was received in August 1975, having spent 10 months in transit.

Although in general the tapes were produced according to instructions there were some awkward variations. Some tapes were only partially perforated, and some were very short. Neither partial perforation nor length causes difficulty on slow 10-characters-per-second tape-readers of the type used in many telecommunication centres, but there are problems with the fast photoelectric readers which are commonly used as computer-input devices. Staff of the DPB performed the painstaking tasks of splicing and reperforating tapes in longer lengths suitable for computer processing.

A few centres had no capability for perforation, and, as planned, their manuscript data were accepted for hand punching at Bracknell.

Real-time data processing and usage

The GATE data obtained through telecommunication channels, together with normal current data, were processed by the SDB suite of programs used for the objective-forecast, chart-plotting and other routine tasks.

The Operations Control Centre for GATE (GOCC) at Dakar needed daily information on how the GATE telecommunication program was functioning. A monitoring program, originally written for the preparation of the United Kingdom statistics for the annual WMO telecommunication survey, was modified to list missing SYNOPs and both missing and incomplete TEMP/PILOTs. A further list of upper-air ascents that failed to reach 400 mb was also prepared. The lists of missing and incomplete reports were issued directly as paper tapes by the IBM 360/195 each day, soon after 11 GMT for midnight and 23 GMT for midday data. They were passed to the Telecommunications Branch and telexed

to Dakar within the hour. This enabled GOCC to take action within about 12 hours to remedy teleprinter faults and to offer immediate technical assistance to non-reporting upper-air stations.

During the operational phase of GATE the Dynamical Climatology Branch prepared analyses and forecasts for tropical areas by using a newly programmed model. The source data for the model were obtained from the GATE-augmented SDB by using techniques developed for the routine 10-level octagon forecast.

Quick look data set

An important aim within GATE was to make data available as soon as possible. To this end it was decided to produce a Quick Look Data Set (QLDS) of meteorological reports. The data set was discussed and agreed at Washington in February 1974. The present writer proposed and presented a format derived from a Basic Data Set Project used previously by the Global Atmospheric Research Program (GARP) of WMO and this was accepted. The programming work was undertaken by the Dynamical Climatology Branch. The QLDS relied on the real-time SDB for its data. However, during the first three weeks of GATE, important TEMP/PILOT reports from ships were not processed because the message format used by some participating countries was not that expected. These reports were included when they were received by post (about a month later) by which time programs had been suitably amended. The conversion to the QLDS format took longer than expected, but was completed by April 1975.

Processing of postal data

As soon as the first paper tapes arrived, they were converted to magnetic tape. By using a library program developed by the Systems Development Branch the PDP11/45 minicomputer produced a magnetic tape for each day of GATE—some 100 tapes in all. These tapes were updated at about monthly intervals as more postal data arrived until August 1975, when all available data had been processed.

The magnetic tapes are at present being processed to augment the SDB Archives. Each daily tape of postal observations is used to augment the SDB created for operational purposes at the time of observation. Any data not recognized by the programs are stored as 'Dregs'. This store contains valuable reports as well as non-meteorological information. Bulletins with incomplete headings and corrupt reports are the most important. Recently Visual Display Units (VDUs) have been added to the Meteorological Office COSMOS computer, and programs have been written within the DPB to display and edit the 'Dregs'. Staff are currently working through the 100 tapes to extract as much information as possible. On completion of this task the data will be processed once more to augment the SDB. This will be the only source of much of the land data for the GATE SSDC Final Data Set and will complement the ships' data received directly from the participating countries.

Results

Comparisons of data available from some trial processing for the Final Data Set show increases of 20 per cent for SYNOP and 35 per cent for TEMP/PILOT reports over the amount available from normal telecommunication channels. There have been regional variations; in particular South American reports were rarely available immediately. Thus the postal contributions have been vital to the project and it would seem that they will be equally vital to any future similar experiment.

551.506.24:551.507.352

MRF IMPRESSIONS OF GATE

By D. B. HATTON*

SUMMARY

An informal account is given of the work of the Meteorological Research Flight aircraft, its crew and supporting staff during the field phase of GATE, with a brief description of the type of data collected and the plans for their analysis.

The realization that MRF were going to meet their target of full participation in GATE came early on the morning of 24 June 1974. Following several months of frantic preparations at Farnborough, caused mainly by the delay of the modified Hercules, the aircraft was finally on its way to Dakar, Senegal. On board were the MRF staff, RAE ground servicing crew and RAF aircrew totalling 28, for the first phase of the experiment; twenty-two days in a country about which very little seemed to be known in England—except that it was hot, and that French was spoken there.

Eight hours later the secrets of the country were beginning to unfold, as the airport immigration and customs officials were encountered. The most important word of French needed was 'le GATE'—this probably solved more problems and tricky situations than any fluent French during the period of our stay. This of course was due to the fact that French was the 'imported' language, and Woolof was spoken by 90 per cent of the population.

The headquarters for our stay were four rooms in the GATE Operational Control Centre building, GOCC, which was just being completed as we, and all the other nations' representatives, arrived. The main briefing room had an echo that resounded for several days to come to the builders' and decorators' work, whilst introductions and initial plans were made. Perhaps this, and the pauses of the interpreters, enabled us all to re-adjust more easily to the new pace of life in this country.

The first tasks for the MRF Hercules were intercomparisons with other aircraft, calibrations against an instrumented tower, and a practice of one of the flight plans before Phase I started in earnest. The aircraft were scheduled to fly two days in three, and initially we had only one crew of observers, so that any free time was obviously going to be at a premium. The flights were for about 8–9 hours, and usually five of these were at low level, on task, so that any flying day was pretty exhausting. Many of our days on the ground were required to get all the flight logs into a form suitable for the data co-ordination section, and many hours were spent initially in reaching the best compromise between the data co-ordination group's requests and our flight procedures.

The temperature in the data-recording compartment where the aircraft experimental instruments are monitored was frequently 35°C, and it was customary to operate with a gallon of water, or fruit cordial, on one side, and drink it all. Sometimes the aeroplane would return covered in salt and red Sahara dust,

* Mr D. B. Hatton is a Higher Scientific Officer at the Meteorological Research Flight, Farnborough. He departed for Dakar in late June 1974 aboard the MRF Hercules and remained there until the end of Phase III, returning towards the end of September. His main responsibilities were concerned with the maintenance and calibration of the meteorological instrumentation aboard the aircraft. As well as this he was a resident member of the MRF flight observer team, clocking up more than 250 flying hours.

or, if we found an active cloud cluster in the operating area, paint would be missing after five hours of rain erosion, and water would run from the instrument covers after flight.

Either way, post-flight instrument care would include washing and drying, while post-flight observer care also included washing and drying, and of course lubrication (thanks to Stork beer). The ground support team then took over, checking flight data tapes for obvious instrument or recorder faults so that, if necessary, repairs could be made before the next flight.

Dakar is a French holiday resort, so restaurants with French-style cooking abound. The Senegalese have been taught this art which has influenced their preparation of local foods as well as the imported ones.

Fish are plentiful in the sea, and fishing communities thrive on them, producing catches of all shapes and sizes, piled on the sand each evening. Some are sold fresh, some are dried in the sun. The communities have an aroma of their own—mixed in with fish odours were the smells of roasting peanuts and maize, fruits, vegetables and grain, and of course open sewers.

Dakar is full of variety. Perhaps the best way to appreciate it is to understand the people, and for that the key lies in the language. Their whole philosophy is different from the European; their reply to a simple greeting 'Hello, how are you?' is 'I'm alive'. Many words just do not exist, and a French and Woolof mixed sentence produces some consternation on ears accustomed to Parisian French. A measure of distance is given in units of 'over there', this phrase being repeated several times as the distance increases! The abounding labourers at GOCC were always enthusiastic about teaching us their language over a cup of tea or coffee, and the effect in the markets was amazing. A reply in the local tongue brought immediate friendship and reduced prices—even the beggars change from 'dix francs' to 'niar (2) francs' in Woolof!

Phase I drew to the finish, everyone being glad that the hardest period, of finding out if such an international exercise would work, was over. With sometimes 10 aircraft and up to 30 ships involved it was an achievement just to obtain the co-operation between the nations, and the amounts of scientific data being collected were enormous. It was with relief that we realized that some of the instrumentation on the other aircraft was as untried as ours, and it was with a certain amount of pride that the aircraft returned to the United Kingdom for servicing, after the first operational phase, knowing that the last-minute preparations had proved successful and reliable.

At this time, many of the ships were heading for Dakar from their various stations out in the Atlantic. Some had just been names on a map to us, some a faint voice over the aircraft intercom, while others were more familiar, being rendezvous or positioning points for the aircraft during the missions away from base. The port now became the scene of considerable activity; what did the gaze of those tethered balloons looking down all day on the people of Dakar mean to them? The rainy season had arrived on time this year—the witch doctors might be upset by the rumours of the 'GATE' rainmakers! Meanwhile, GOCC was having its 'spring clean' with grass and flowers appearing overnight, to herald the official opening of the building by the President of Senegal on 23 July.

With this formality over, the ships set sail for their stations, and the aircraft were soon returning, bringing with them some new faces and some familiar. Many of the initial teething troubles were overcome as Phase II began.

The air was much clearer now and the ground had a green sheen of new growth, as Dakar came under the influence of the Intertropical Convergence Zone. Sometimes we would fly south to the equator, leaving the towering cumulonimbus clouds behind, and passing over seas that reflected like a mirror the small cumulus clouds, a rare sight at England's wind-swept latitudes. Often at 500 ft or lower, we were measuring boundary-layer fluxes, with flying fish and whales for company. Other days we might visit the ship arrays to intercompare with the instruments on the tethered balloons. Phase II finished with an intercomparison between many of the ships—how strange to see such a vast fleet of ships lined up, and for peaceful purposes!

Dakar was probably at its wettest now, with rain in the form of showers in squall lines every few days. Further south the countryside grew rapidly greener; here was the 'Garden of Senegal', the region of Casamance, where tropical rain forests thrived in semi-continuous rain at this time of year, and much of the land was cultivated to grow rice, fruits and groundnuts. It was not hard to understand why some French people remained when the country became independent. Disease is probably the biggest drawback to living here, an observation borne out by the large numbers of small children, and the lack of adults over about forty.

At the end of August Phase III was about to start, with the addition of a few ships and aircraft. An emphasis on sea surface measurements due to the oceanographic bias of this phase necessitated the addition of one more instrument, an upward-facing infra-red radiometer, to the MRF Hercules during its interphase servicing absence. The airport authorities were now as familiar with the aircraft procedures as they ever would be. Several aeroplanes leaving within a few minutes of each other, or arriving back together after a mission, sometimes brought a little confusion, but the air traffic controllers always had the priorities right. A good example occurred one morning when several GATE aircraft had their engines running and were ready to taxi. The order came to stop engines while the President's aircraft departed. It is not etiquette to have the propellers turning while he passes.

So with only a few delays the flights went as planned, finishing with aircraft intercomparisons and another dreaded tower calibration. This tower was an open lattice construction, 120 ft high, with instruments to compare against aircraft height, temperature and dew-point measurements, erected on a disused airfield. The aircraft had to be flown to a height accuracy of about 20 feet, within a few wingspans of the tower, at various airspeeds within its operating range. It was a brave man who sat on top of the tower and judged whether the aircraft height was within the prescribed limits for each pass. From experience, there are many better places to be in than the cargo hold of a Hercules during such operations, considering the turbulence and acceleration forces resulting from tight turns and positioning corrections required to keep on track over the hot desert countryside. The relaxation at a farewell party was earned that evening. Three months was long enough for an experiment on such a large scale; everyone would still part as friends. Suddenly, hotel service became more efficient, waiters were always hovering expectantly and rooms were cleaned several times a day. Even the porters at GOCC were awake most of the time! The news had spread, GATE—a word that meant work for many in our host country —was over.

For MRF, however, the work was by no means over; 43 flights collecting

data at 640 samples a second means that something in the order of 750 million words of data have been recorded. This has to be transcribed by the PDP8/I computer at MRF on to working magnetic tapes and then checked through to ensure that it is all valid before any processing can take place. The outputs from each instrument must be examined for errors and the appropriate calibrations applied. Derived parameters, e.g. wind and humidity are then evaluated from the basic measurements. All these data have then to be assembled in an internationally agreed format, for storage in the GATE world data centres in USA and USSR, and for use by the five subprogram data centres located in various participating countries. This is no small task as MRF had not established a comprehensive data-handling system for the Hercules prior to GATE, this being the aircraft's first experimental mission.

Computer programs have now been written to cope with the large number of different processes carried out on the data. A typical flight requires two passes through the master tapes to extract and process all the data. The reason for this is that there are two distinct requirements, firstly averages over 1 minute and 1 second for the whole of the flight and secondly 20-Hz data for the 'operational' part of the flight. The bulk of the processing is being carried out initially on the ICL 1904A at the RAE, and at present each flight requires about 40 hours of computer time. This assumes that there are no interruptions due to program or computer faults, or any other gremlins that manage to lurk so easily among 9000 million data bits! Considerable patience and ingenuity have been required to cope with the problems encountered during the development of these programs. A year after recording them, reliable methods of processing the data are still being finalized and at such times MRF impressions of GATE are rather different from those gained in West Africa. It isn't easy to decide whether the collection or extraction of GATE data will leave the most lasting impressions, and it will be many months yet before we know.

Illustrations of an MRF aircraft before and after the exercise are to be found in Plates II and III.

Short glossary of words and expressions occurring frequently in special GATE issues

platform—A structure to which measuring instruments are attached; it may be stationary (e.g. an ordinary ground station) or moving (e.g. a ship, aeroplane, balloon, or satellite).

data set—A set of data stored in a rigorously specified and consistent manner in a storage medium, such as magnetic tape, that can be read and processed by a computer.

format—The arrangement of numerical and other data in groups with exact correspondence between the position of a number or character in a group and its meaning.

validate—To check that data are arranged in the correct format and that all implied values of variables are reasonable and mutually consistent.

flag—An indicator placed in close association with a particular value of a variable occurring in a data set to show that this value is suspect or otherwise merits special attention.

real time—An expression used to refer to any system in which the processing of data that are input to the system to obtain a result occurs almost simultaneously with the event generating the data.

DR G. M. B. DOBSON, C.B.E., F.R.S.

Dr G. M. B. Dobson, formerly Reader in Meteorology in the University of Oxford, died on 10 March 1976 at the age of 87.

Gordon Miller Bourne Dobson was born in 1889, son of Thomas Dobson, M.D. of Windermere, and was educated at Sedbergh School, and at Caius College, Cambridge. Dobson's first job was as student-assistant at Kew Observatory in 1911, and was arranged between Sir Napier Shaw and Gonville and Caius College, Cambridge, the college providing a £50 per annum studentship and the Meteorological Office an assistantship. His terms of appointment as detailed in a letter from Shaw were as follows: 'The ordinary hours of attendance at the Observatory are, I believe, 9.30 to 5, with a half holiday on Saturday and a month's holiday in the year, but in my experience the exigencies of research pay little attention to office hours and if one wants to find out anything one has to take the opportunities that offer, so that the rules as to hours in this case would have to be sufficiently elastic to be comprehensive as well as reasonable'. Dobson stayed at Kew until 1913, during which time he carried out some investigations of atmospheric electricity and also spent some time with L. H. G. Dines at Eskdalemuir.

In 1913, after a short time at Kew Observatory, Dobson joined the Central Flying School at Upavon as Lecturer in Meteorology, and it was here that he carried out a classic set of balloon experiments on the upper winds, in the results of which G. I. Taylor (later Sir Geoffrey) at Cambridge was very interested. During the First World War he was head of the Physics Section at the newly formed Royal Aircraft Establishment at Farnborough where he met F. A. Lindemann (later Lord Cherwell). In 1920 he joined Lindemann at the Clarendon Laboratory, Oxford. Together they studied meteor trails, and this investigation led to the discovery of a region of high temperature at an altitude of about 30 miles. Since ultra-violet sunlight absorbed by the stratospheric ozone layer was thought to be responsible for this, Dobson set about the measurement of atmospheric ozone, work on which he was to continue for the rest of his life and for which he became internationally famous.

In order to make accurate measurements of stratospheric ozone he developed new techniques for ultra-violet spectroscopy and built the first photo-electric microphotometer for measuring photographic plates. With D. N. Harrison and I. O. Griffiths he wrote a textbook on photographic photometry in 1926. In the 1930s Dobson set up a world-wide network of ozone measuring stations, much of which is still in existence, employing the Dobson instruments.

In the early part of the Second World War a method was required of forecasting the conditions under which condensation trails would be formed by aircraft. In co-operation with A. W. Brewer, Dobson designed an instrument for measuring water vapour from aircraft. With the instrument they developed, known as the Dobson–Brewer Frost-point Hygrometer, which is still in use today, the first measurements of the very low water-vapour content of the stratosphere were made in 1943. Some of the early work on the freezing of cloud droplets was also carried out by Dobson and his students at Oxford.

In 1927 Dobson was elected a Fellow of the Royal Society, whose Rumford Medal he was awarded in 1942. Merton College elected him to a Research Fellowship and the title of Professor was conferred on him by the University. He was President of the Royal Meteorological Society from 1947 to 1949.

In the late 1930s Dobson was chairman of a committee of the Department of Scientific and Industrial Research set up to investigate atmospheric pollution. In 1941 he was one of the founder members of the Meteorological Research Committee, a body set up to bring together the expertise of academic meteorologists in universities and the research scientists in the Meteorological Office. Dobson was chairman of the committee from 1947 to 1952.

Much of Dobson's work was carried out in his laboratory at his homes in Oxford, first on Boar's Hill and later on Shotover. His main recreation was cultivating his large garden. After retirement in 1956 he carried on his observations on ozone, his last scientific paper being written in 1973. He was an active member of St Aldate's Church in Oxford, being a churchwarden there for many years.

All Dobson's students and colleagues will remember his unique skill as an experimental physicist; we have all benefited from being exposed to his very practical approach both to his science and to his life as a whole. We extend our sympathy in their loss to his wife, his two sons, and his daughter.

J. T. HOUGHTON

NOTES AND NEWS

Retirement of Mr L. P. Smith

Mr Lionel P. Smith, Special Merit Senior Principal Scientific Officer, retired from the Office on 6 May 1976 after some 38 years' service. Mr Smith gained B.A. degrees at Oxford University (Queen's College) in mathematics and physics and his official career commenced with postings to Kew Observatory and Croydon where, like most of his contemporaries, he received a rather informal professional training before serving as a forecaster at Croydon itself and then at a number of RAF stations in the United Kingdom throughout the Second World War. It might not be generally known that he qualified for membership of the Caterpillar Club as a consequence of his parachute escape from a Stirling bomber over Northern Ireland in 1944.

In 1946 Mr Smith commenced a three-year tour of duty overseas, serving firstly in the Levant and finally as Deputy Chief Meteorological Officer at Ismailia. He returned to the United Kingdom in 1949 to become Head of the then newly formed Agricultural Meteorology Branch and entered an area of activity which was to dominate the remainder of his career in the Office. It was not long before he became well known in agricultural as well as meteorological circles, partly because of his contributions to the solution of practical farming problems where the application of weather-based intelligence was appropriate and partly as the result of his publications in agricultural as well as the more familiar meteorological journals. In 1954 Mr Smith was awarded a Nuffield Travelling Fellowship which enabled him to visit Canada, New Zealand, Australia, the Republic of South Africa and most countries of western Europe to study their methods and progress in agricultural meteorology and allied fields. His reputation grew steadily throughout the fifties and in 1960 he was given Special Merit promotion and became completely free to devote his time to his main interest. His tenure of office as Head of the Agriculture Branch saw the establishment of outstations in some of the regional offices of what is now the Agricultural Development and Advisory Service of the Ministry of Agriculture, Fisheries and Food solely devoted to providing meteorologically based advice in the broadest sense for agricultural practitioners.

Over the 15 or so years following his Special Merit promotion, Lionel Smith continued to apply himself wholeheartedly to his subject and became a much-respected and sought-after contributor and participant in the international as well as the national sphere. He served two terms (1962–71) as President of the WMO Commission for Agricultural Meteorology and wrote many WMO reports and technical notes as well as acting as an organizer and lecturer at WMO-sponsored training seminars and the like. Throughout this period he published many scientific papers and a number of reports and received several awards including the L. G. Groves Memorial Prize for Meteorology in 1965 and the Clive Behrens Lectureship at Leeds University in 1965–67. His activities continued unabated until his retirement, by which time he had some 200 papers, reports, books etc. to his credit. His latest book 'Methods in agricultural meteorology' contains a distillation of his wide experience extending over a quarter of a century, and reflects his breadth of knowledge, humour, strongly held views and forceful but none the less fundamentally sympathetic attitudes. Above all, L. P. Smith is one of the outstanding characters of his generation of meteorologists. Although he has now officially retired it is certain that we have not heard or seen the last of him. His colleagues at home and overseas will miss the inspiration and stimulation which flowed in full measure from an extremely dedicated worker. We wish him a happy, and above all, an active retirement.

N. E. RIDER

COST 72 Technical Conference on Automatic Weather Stations

A Conference and Exhibition dealing with Automatic Weather Stations (AWS) will take place at the University of Reading, Berkshire from 22 to 24 September 1976. The event is the culmination of a study on the use of AWS in a group of European countries whose governments are participating in European Co-operation in the field of Scientific and Technical Research (COST).

Papers describing experiences of existing AWS systems and the problems and requirements of future systems have been promised from several countries including the German Federal Republic, The Netherlands, Finland, Yugoslavia and the United Kingdom. The Exhibition will have equipment from manufacturers of AWS systems and sensors, and exhibits from user organizations.

Further information may be obtained from

The Chairman of the Programme Committee,
COST 72 Technical Conference on Automatic Weather Stations,
Meteorological Office (Met.O.17),
London Road,
Bracknell,
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NOTICES

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THE UNITED KINGDOM METEOROLOGICAL OFFICE OBJECTIVE ANALYSIS SCHEME FOR GATE

By D. E. JONES

(Meteorological Office College, Shinfield Park)

SUMMARY

The objective analysis scheme devised for the numerical forecasts that were run in near real time over the GATE area was an adaptation of the optimum interpolation method first described by Gandin. Data extraction and analysis of wind and geopotential were carried out on p-surfaces with subsequent interpolation to σ-surfaces, mutual adjustment between wind and geopotential fields being produced by use of numerical variational analysis. Humidity analyses were carried out directly in σ-coordinates. Data of all types were used, including satellite soundings and aircraft reports. The methods of error assessment for optimum interpolation are briefly described, and an account is given of the types of quality control applied to the raw data. Comparisons of some objective and subjective analyses show that the results of the techniques adopted are encouraging.

1. INTRODUCTION

Before the Tropical Research Group in the Meteorological Office were able to take the unique opportunity of the GATE experiment to use real data for testing their numerical modelling of the tropical atmosphere by comparisons with the real atmosphere, the data needed to be transformed into a form that could be handled by the prediction equations. This task was carried out by an Objective Analysis Group in the Forecasting Research Branch. The requirement was to develop an objective analysis scheme to assimilate as many different types of data as possible by means of a quasi-operational objective analysis scheme which was to be run every 12 or 24 hours, less than a day after observation time, with the 12- or 24-hour forecast providing the background field for the next analysis. The Tropical Research Group needed the surface pressure, upper-air temperatures and winds in σ-coordinates ($\sigma = p/p_*$, where p_* is the surface pressure), and humidities by layers of the σ-coordinates. The area to be covered extended from 35°N to 15°S and from 77°W to 49°E. A latitude/longitude grid was used with a spacing of 2°.

Because of the northerly latitude reached by the analysis area, and perhaps also the mid-latitude experience of the Objective Analysis Group in the Forecasting Research Branch, it was decided that a certain amount of balancing between the wind and the mass fields was desirable before the dynamical initialization process. It seemed advantageous to do this at a stage when adjustments to the two fields could take into account information concerning data density and the reliability of the analyses. This information was available because estimates of the error variance of the analyses were obtainable from the basic optimum interpolation analysis scheme that was used. The adjustment scheme used required the solution of the Balance Equation in reverse (mass field from wind field), and since our previous experience had not extended to solving this in σ-coordinates it was decided to carry out the basic analyses of mass and velocity in pressure coordinates, adjust the fields, and then interpolate into σ-coordinates. Analyses of geopotential and wind components were performed at pressure levels 1000, 950 (height only), 850, 700, 500, 400, 300, 250, 200, 150, 100 and 70 mb. It was originally intended to include the 30- and 10-mb levels but the quality and quantity of data were too poor and climatological values were used instead.

There are other reasons for including an adjustment step besides the reduction of amplitude of initial gravity waves. The basic analyses of each variable were obtained by interpolation from observations of the particular variable, using the process of optimum interpolation, which will be outlined later. The interpolation at each point required the solution of a number of simultaneous linear equations equal to the number of observations used, therefore the number of observations used to interpolate at each point needed to be limited for economy reasons. This introduced into the analyses roughnesses which needed to be removed. Also, by using some diagnostic relationship between the wind and mass variables, the adjustment process allowed values of one variable to help with the analyses of the other variable; this was important in areas where data were sparse. In particular there were often large numbers of satellite wind vectors available in areas where there were few reliable observations of geopotential, for instance, over central South America and the south-western parts of the tropical Atlantic, and here the adjustment process enabled the wind observations to influence the shape of the analysed geopotential field. In the objective analysis scheme for the 10-level model, only geopotential analyses are produced, and the wind observations influence these analyses directly through the geostrophic or gradient-wind equations.

The analysis scheme was followed by an initialization process which is described elsewhere in this issue, and the cycle of analysis, initialization and forecast can thus be summarized as follows:

(a) Derive wind and height background fields from previous forecasts which verify at time T, by interpolation from σ- to p-surfaces, except for relative humidity which was for model σ-layers.

(b) Extract data for time T.

(c) Adjust background fields in the light of the observational data, and mutually adjust the wind and geopotential fields using a variation analysis technique to give a preliminary set of analyses. After study of

data and analyses by a monitoring team, insert corrections and bogus data as required and repeat analysis for wind and geopotential fields to give final analyses.

(d) Interpolate from wind and geopotential fields and pressure surfaces to wind and temperature fields for σ-layers and surface pressure.

(e) Reduce high-frequency waves by mutual adjustment of wind and mass fields in dynamical initialization step.

(f) Use model to advance fields from time T to time $T + 12$ (or 24).

2. Data

The data used came from radiosondes from ship and land stations, satellite sounding reports (SIRS), upper winds and pilot balloons, radar, rawinsondes or LOCATE systems, aircraft reports, satellite cloud vector reports (ATS and GOES), and surface reports from ships and land stations. The data extraction programs were written by members of the Dynamical Climatology Branch and a certain amount of quality control had been done by the time the objective analysis programs were employed.

Analyses were carried out at fixed times, and data were used provided that their observation time was within three hours of the time for which the analysis was valid. No attempt was made to adjust off-time observations in any way at all except by reducing their weight (increasing their error variance) as their time discrepancy increased.

Wind reports from aircraft were used at the two nearest analysis levels, one above and one below, and were adjusted to take into account the vertical wind shear as estimated from forecast values available from the background fields. High-level and low-level ATS winds were allocated to the 250-mb and 850-mb levels respectively. SIRS data were corrected for excessive warmth, corrections varying from 20 m at 850 mb to 40 m at 500 mb and 110 m at 70 mb.

After the 100-mb and 70-mb analyses had been carried out, all radiosonde reports of geopotential at these levels were compared with the analysed fields and the differences found were interpreted as being caused by the complete sounding being systematically warm or cold. Fractional corrections were then made to the observed values at the lower levels as in the analyses for the 10-level model.

3. Error assessments for optimum interpolation

In optimum interpolation, the method used for obtaining grid-point values, each observation used and each background field value is given a weight that depends, among other things, on the reliability of the observation and of the background field. The more reliable they are, the greater their weight, so that considerable effort went into the assessment of the variance of the errors both of the observations and of the background field. Values used were assessed from the literature, but it is important to note that the error variances required by the optimum-interpolation process are not solely dependent on instrumental errors but have to include the effects of scales of motion which are too small to be represented on the grid used; this is termed 'noise' and the optimum interpolation scheme assumes that this noise has no spatial correlation. For each

wind component a noise value of 9 $m^2 s^{-2}$ was added to the estimated instrumental variances (Alaka and Elvander, 1972). For values of geopotential obtained from radiosondes, values were taken from Rutherford (1972). The net effect of noise is to reduce the weight of the observations. The assessment of errors of background fields was problematical because none of these forecasts had ever been run on real data, so that estimates had to be made from our experience with the 10-level model and from statistical studies of the temporal variation of meteorological fields in the tropics.

4. Data checking

All the data had undergone quality-control checks before the objective analysis programs were reached, but a further check was introduced before data were used in the analysis. An interpolated value was obtained at the observation point using the background field and observations other than the one in question. The observation of a variable was rejected if the difference between the observed value and the interpolated value was greater than a quantity which itself depended on the reliability of the interpolated value. The criterion was based on the theory of Maximum Likelihood. In areas of plentiful observations the interpolated value will be fairly reliable and therefore a small departure from this on the part of the observation is sufficient reason for its rejection. On the other hand, in an area of few observations the interpolated value itself is unreliable and a large difference may be due to the unreliable analysis, and therefore one should accept observations in this area more readily. The process for accepting or rejecting observations is a most important part of any objective analysis scheme. One of the fundamental problems of objective analysis—or for subjective analysis for that matter—is the decision whether or not to reject a particular observation which deviates markedly from a forecast background field; it is difficult to decide whether it is a very bad observation, or one of the most valuable observations because it indicates that the background field is very badly in error.

In spite of these checks a considerable amount of human monitoring was required to correct erroneous reports, or to insert artificial ones where this was thought desirable. Considerable difficulty was encountered over the mountainous regions of East Africa, over South America, and the south-western parts of the tropical Atlantic and round the boundary of the analysis area. In general, analyses were not amended subjectively unless they contained features that were obviously unrealistic.

5. Analysis technique

The analysis of relative humidity was obtained using the scheme described by Atkins (1974). This is based on Cressman's successive-approximation method in that it uses a weighting function which depends on the distance of the observation from the grid point, but a major difference is that the weighting function is anisotropic in that it also depends on the gradient of the background field, i.e. on the 12- or 24-hour forecast. The weighting function falls off more rapidly in directions across the contour lines of the background field than in directions along the contour lines. This helps to preserve the patterns existing in the background fields and was found to be very advantageous in mid latitudes.

The analysis process for the geopotential and winds is in two stages. First

there is horizontal interpolation to obtain values of geopotential and wind independently at each grid point, and this is followed by the 'adjustment stage', which allows the two fields to influence each other.

For the first stage, the method of optimum interpolation was used. Optimum interpolation was first described by Gandin in 1963 but it has undergone a number of developments and a recent description has been given by Kruger (1969).

As with most objective analysis methods, optimum interpolation combines the observations with a first-guess field which provides an analysis value in areas where there are no observations but which becomes less important (i.e. has less weight) in areas where observations are more numerous. The observations are used to correct the first guess. The difference between each observation and the background field at the observation point gives us an estimate of the error of the background field at this observation point. If we have a number of observations near to, and preferably surrounding, a particular grid point then we can combine these error estimates to form a correction to the background field at the grid point; this is the process of interpolation. Obviously if the observation point is close to the grid point it provides a more reliable correction to the grid-point value and therefore deserves more weight than an observation further away. The rate at which the weight should fall off with distance depends on the spatial coherence of the background error field; if the error field is 'spotty', so that the error at one point is not correlated with the error a grid length or two away, then the weight falls off more rapidly than if the errors are on a fairly broad scale. Knowledge of the characteristics of the error fields both in their magnitude and in their scale is important in many analysis schemes and is certainly very important for optimum interpolation.

The weight given to an observation depends also on a number of other factors. For instance, reliable observations get more weight than unreliable observations and because of this we need to have estimates of the variances of the errors of each type of observation. Also observations get more weight if the background field is thought to be unreliable.

In optimum interpolation the weights given to the observations (or rather the weight given to the estimates that they provide of the error of a background field) also depend on one other factor—how close observations are to other observations. Obviously if one is using, say, four observations to interpolate a value at a grid point it is better that the observations should surround the grid point rather than cluster all together on one side of the grid point. Optimum interpolation allows the weights to take into account the presence of other observations.

The mathematics is complex, but optimum interpolation allows us to calculate the weights, taking all the above into consideration, which, in a statistical sense, provide the best (optimum) estimate of the grid-point value from the given distribution of observations and the assumed reliability of the background field. Once the weights are determined it is possible to estimate statistically the variance of the error of the analysis at the given grid point.

The observations are used essentially to provide estimates of the errors of the background field, so that it can be corrected. Information on the spatial interrelationship of these errors has to be provided in the form of spatial correlation functions of the errors. If many forecasts had been available, these

functions could have been calculated empirically. However, since no forecasts had in fact been carried out, the functions were given the form

$$R(r) = \frac{1 - r^2/2\lambda}{(1 - r^2/\lambda)^{5/2}},$$

where $R(r)$ equals the value of the correlation function for given r, r = distance between observations or between observation and grid point, and λ = a constant which determines how broad or how narrow the curve is. The shapes of the curves are similar to those given by Atkins (1970) and resemble a 'cocked hat'. λ was chosen so that $R(r) = 0$ at 2000 km; this gives a broader function than is really true for fields in the tropics, particularly for the wind field, and results in a smoothing of the analyses. This seemed desirable in view of a lack of experience at that time.

The number of observations used for estimating the value at each grid point was kept to 8; several experiments had shown that raising the number to 12 made very little difference to the interpolated values and thus did not warrant the doubling of the work involved. In fact if there are several observations close to the grid point it is likely that a smaller number still would suffice. Where possible the 'nearest' two observations in each quadrant about the grid point were chosen, where the 'distance' was given by

$$\frac{R(i,g)}{1 + \dfrac{\sigma^2 \text{ errors of observation}}{\sigma^2 \text{ errors of background}}},$$

where $R(i,g)$ is the value of the correlation function between the observation point and the grid point, and the σ^2 are the variances of the errors of observation and of the errors of the background field. This allows a good-quality observation to be selected even though it is somewhat further away from the grid point than another observation which is less reliable.

6. Adjustment stage

Up to this point the analyses of geopotential and wind are independent of each other, apart from the fact that the background fields of both are derived from the forecasts from the prediction model. It is known that in middle latitudes, it is desirable, when use is made of the primitive equations, for the initial wind and geopotential fields to be related to each other in such a way that the forecasts start smoothly. This relationship is described mathematically by the Balance Equation, and it can be shown that if this equation is satisfied along with one or two other conditions, then there will be no generation of spurious gravity waves, which show up as rapid variations of surface pressure in the first few hours of the forecast. The procedure used for the 10-level model is to analyse the geopotential field (with the aid of the wind observations as interpreted by the geostrophic and gradient-wind approximation) and then to use the Balance Equation to derive a suitable wind field from the geopotential field. Now since the Balance Equation is rather like the geostrophic-wind equation with additional terms representing the effects of curvature and diffluence, as in the gradient-wind equation, the winds derived from the Balance Equation become unrealistic as one approaches the equator. However, it is

quite possible, and in fact it is easier, to obtain a geopotential field from the wind field in low latitudes using the Balance Equation and use is made of this fact.

The adjustment used is based on the numerical variational analysis due to Sasaki (1970) using a form of his 'weak constraint' in his 'timewise localized' form. First of all a geopotential field h_B is obtained from the analysed wind field, $\mathbf{V}^I$, by solving the Balance Equation in reverse, the effects of friction being allowed for at 1000 mb. Using a mathematical technique called the Calculus of Variations, we then find fields of geopotential and wind (called the adjusted fields) which are similar to the analysed fields but are nearer to a balanced state than the original fields. The process is described in more detail in the Appendix. An important feature is that in areas where one or other of the fields is estimated to be reliable, it is little changed, but where one analysed field is estimated to be rather unreliable compared with the other it will undergo greater adjustment.

Some comparisons of velocity and geopotential fields before and after the variational step show that the two fields are modified in a reasonable way. Since the solution of the Reverse Balance Equation is very smooth in low latitudes the net effect is a smoothing of small-scale features in the geopotential field unless they correspond to features in the wind field. Further away from the equator smoothing is still present but the two fields interact in a more positive way.

7. Complete scheme

The process described so far is applied independently at each analysis level in the atmosphere. Figure 1 shows the outline of the complete scheme. The first level analysed is 1000 mb—this is required to provide a reference level for the SIRS data. Next follow the 70-mb and 100-mb analyses, each followed by radiosonde corrections in the same manner as for the 10-level model (Atkins, 1970). Analyses at 850, 500 and 250 mb are then made simultaneously and the results of these levels are used to adjust the background fields of geopotential and winds at all the remaining levels, thus ensuring a degree of vertical consistency; this also reduces the number of levels at which bogus data need to be inserted when the intervention team decide that analyses require amending.

8. Some results

The remaining diagrams show comparisons of wind data, objective analyses and subjective analyses, the latter being made in Dakar during the GATE period. They are shown for 12 GMT, 2 September 1974 for 1000 mb. The objective and subjective analyses show good agreement, but details of the smaller-scale features such as convergence lines and centres differ. The subjective analyses are neater and more consistent in these areas than the objective analyses, but nevertheless the latter are reasonably consistent with the existing observations.

9. Summary and comment

There is undoubtedly much room for improvement. In particular more attention should be paid to the vertical structure and hence to the temperature and

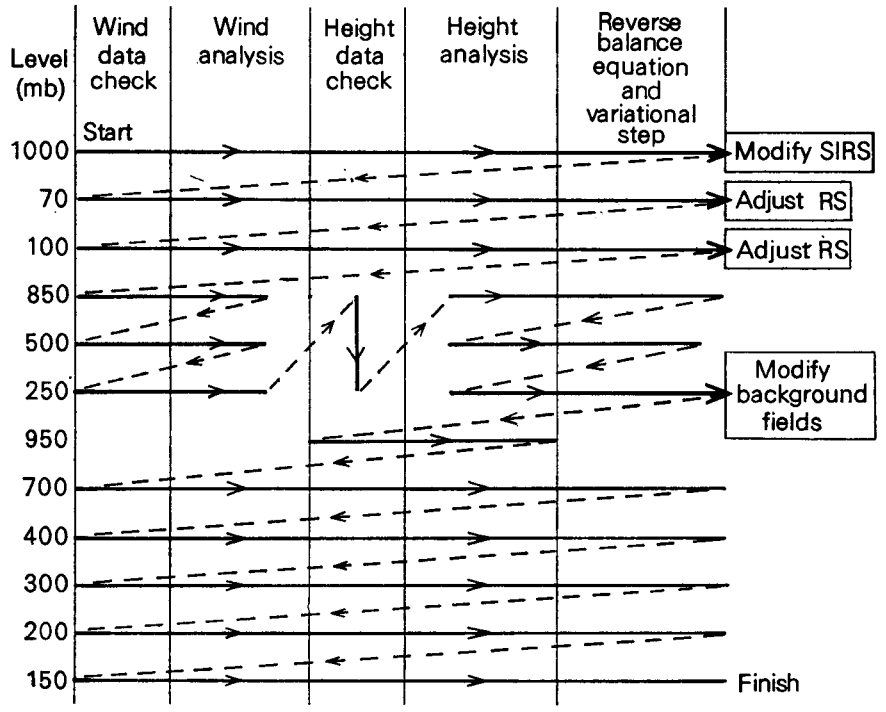

FIGURE 1—GATE ANALYSIS—OUTLINE

RS = radiosonde; SIRS = Satellite Infra-red Spectrometer Sounding.

stability fields. It would also be better if the analysis were done in σ-coordinates since the interpolation to and from the pressure-coordinates system gives rise to considerable roughnesses in the fields presented to the time integration, particularly near mountainous regions.

Analysis of meteorological charts in tropical regions is normally a highly subjective process. Most hand-drawn analyses are limited to representation of flow patterns by streamlines and isotachs, and consistency in time is difficult to achieve. Investigations by the Tropical Research Group in the Meteorological Office show that in these analyses and forecasts there are trough lines which keep a reasonable progression and consistency over a period of several days, and this is very encouraging.

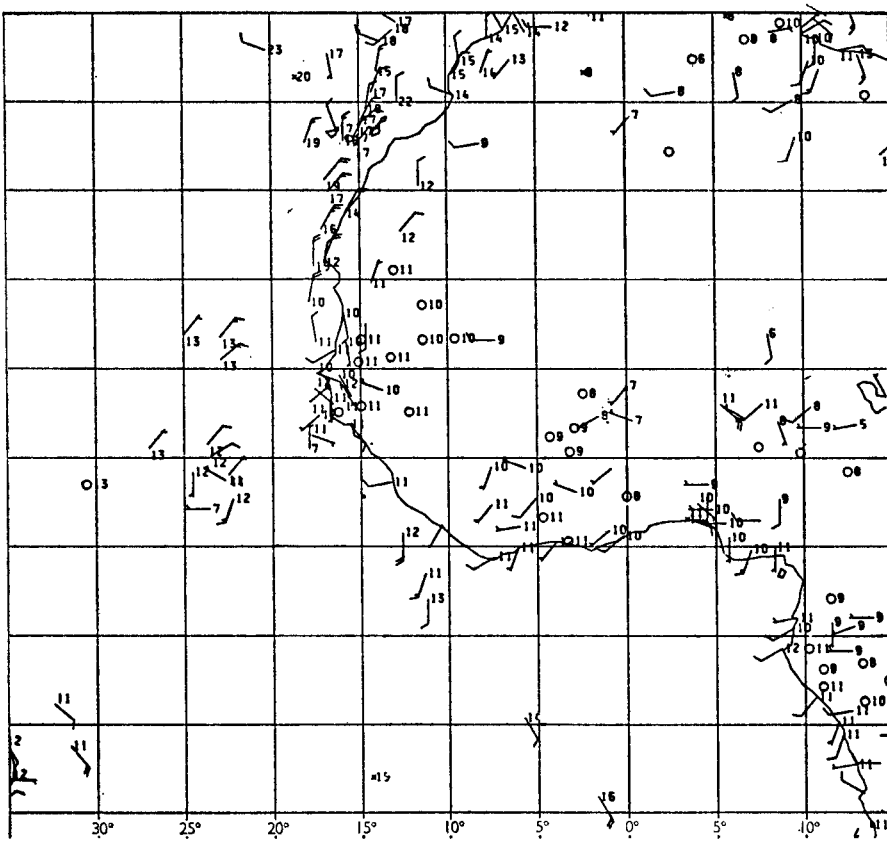

FIGURE 2—DATA FOR 1000 mb AT 12 GMT ON 2 SEPTEMBER 1974

1000-mb heights in metres. Each full feather denotes 5 m/s.

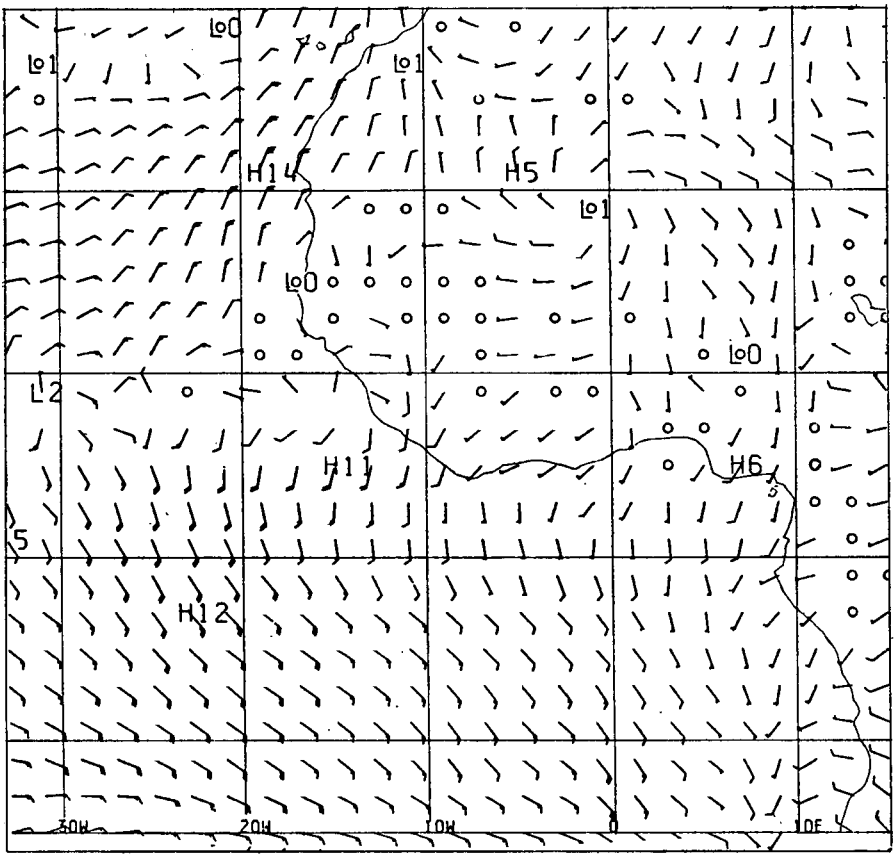

FIGURE 3—PART OF OBJECTIVE ANALYSIS OF WIND FIELD AT 1000 mb AT 12 GMT ON 2 SEPTEMBER 1974

Each full feather denotes 5 m/s.

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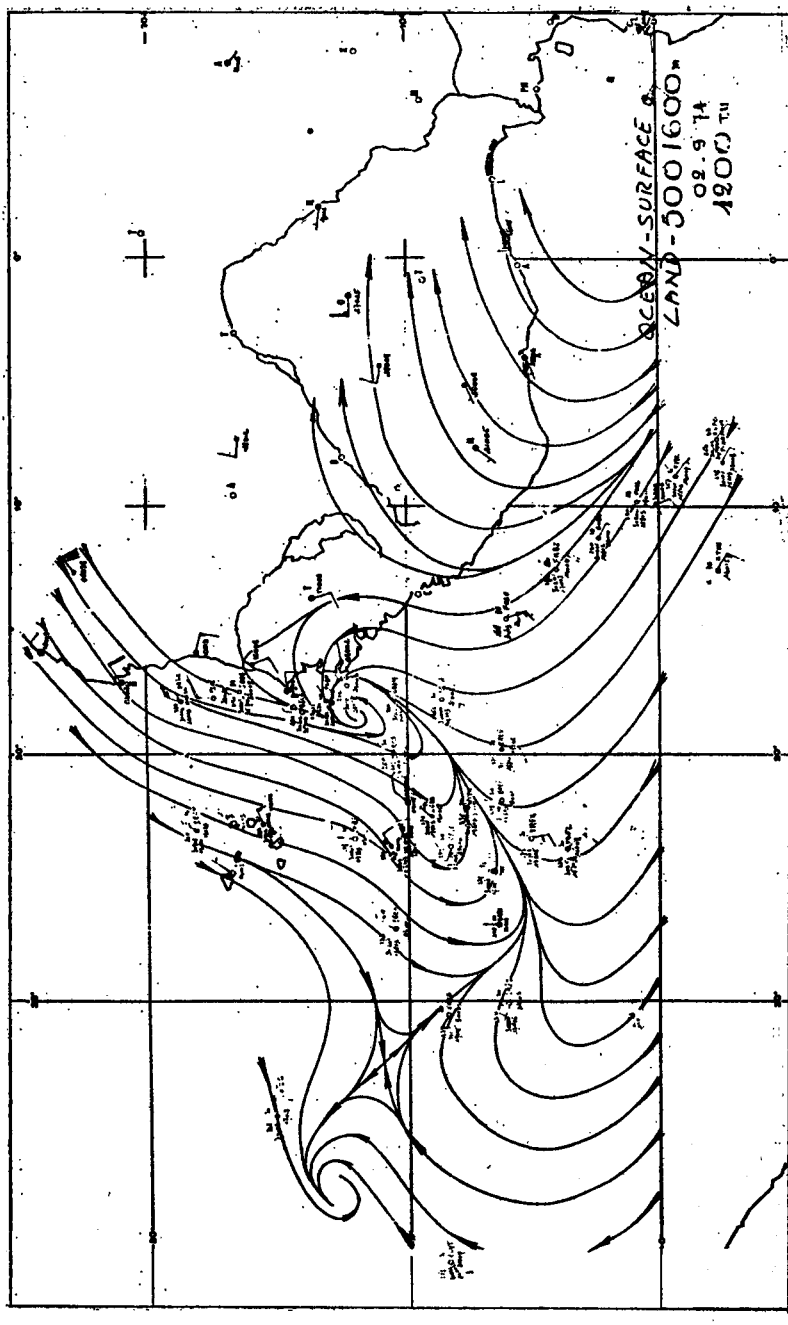

FIGURE 4—SUBJECTIVELY ANALYSED STREAM FUNCTION AT 12 GMT ON 2 SEPTEMBER 1974

Surface wind over ocean, 500–600-m wind over land.

APPENDIX—THE SASAKI ADJUSTMENT STEP

First of all a geopotential field h_B is obtained from the analysed wind field, $\mathbf{V}^I$, by solving the Balance Equation in reverse. The following integral is then required to be minimized, where the integration is taken over the whole area:

$$I = \iint [\alpha(\mathbf{V} - \mathbf{V}^I)^2 + \beta(h - h^I)^2 + \lambda' \{g\nabla(h - h_B) + f\mathbf{k}\wedge(\mathbf{V} - \mathbf{V}^I)\}^2]dxdy,$$

where $\mathbf{V}$ = final (adjusted) value of the velocity field,
h = final (adjusted) value of the geopotential field,
h^I = (initial) analysed value of the geopotential field, and
$\mathbf{k}$ = unit vertical vector.

The minimization required is with respect to variations of $\mathbf{V}$ and h; the parameters α, β and λ' are determined before the integral is minimized. The first two terms keep the departures from the analysed fields to a minimum. Bearing in mind the fact that h_B and $\mathbf{V}^I$ satisfy the Balance Equation, the third term requires that the departures of $\mathbf{V}$ and h from the Balance Equation solution should be approximately in geostrophic balance; because the weak constraint form is used, the geostrophic balance is not actually enforced, and the extent to which the constraint is satisfied depends on the size of λ' relative to α and β. Note that near the equator the term $\mathbf{V} - \mathbf{V}^I$ will be negligible; thus $\mathbf{V}$ will be very close to $\mathbf{V}^I$; the absolute value of h will be close to h^I, but the shape (gradients) of h will be close to h_B.

The variational analysis is straightforward and we are required to solve the following elliptic equation:

$$\nabla \cdot (r\nabla h) - \beta h = \nabla \cdot (r\nabla h_B) - \beta h^I,$$

where $r = \dfrac{\lambda' g^2 \alpha}{\alpha + \lambda' f^2}$.

Suitable boundary conditions are obtained by setting $h - h^I = 0$ round the edge.

The weights α and β are taken as being inversely proportional to the estimated variance of the error of the relevant analysis at each particular point. These parameters therefore vary over the grid and where either of the analyses is regarded as reliable it will not be changed by very much; where one of the analyses is regarded as being unreliable it will tend to be altered to make the constraint more closely satisfied. The values of α and β were of course obtained from the optimum interpolation process. λ' was taken as a constant and a fairly small value was chosen so that fields were not modified except where the error variances indicated that they were particularly unreliable. When the modified values of the geopotential field have been obtained the new values of the velocity field are obtained from the expression

$$\mathbf{V} - \mathbf{V}^I = \frac{\lambda' g}{\alpha + \lambda' f^2} f\mathbf{k}\wedge\nabla(h - h_B).$$

Note that when f is small, $\mathbf{V}$ is virtually independent of the correction to the geopotential field. When λ' is large the relationship reduces to a geostrophic relationship between $\mathbf{V} - \mathbf{V}^I$ and $h - h_B$.

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NUMERICAL MODELLING USING GATE DATA

By W. H. LYNE, P. R. ROWNTREE, C. TEMPERTON and JULIA M. WALKER*

SUMMARY

During GATE an 11-layer primitive-equation model was run in near real time to produce forecasts for up to 24 hours ahead. The flow and rainfall patterns were forecast fairly well apart from a tendency to develop spurious small-scale features. There is a discussion of the possible causes of these and of some systematic errors in the predicted vertical structure of the atmosphere.

INTRODUCTION

The Meteorological Office Tropical Modelling Group was set up at about the beginning of 1973 to develop improved techniques for simulating the tropical atmosphere in the Dynamical Climatology Branch's general-circulation models. Formation of the Group at this time allowed it to take advantage of the data obtained during GATE in summer 1974. A limited-area version of the global model then being developed in the Branch was constructed centred on the GATE B-scale area so that forecasts could be made for up to three days without serious contamination of the B-scale area forecast by boundary effects. Forecasts from analyses based on GATE data could then be made with different versions of the model and the quality of the simulations so obtained could be assessed by comparing them with reality.

Creation of satisfactory initial analyses required suitable data-extraction, analysis and forecast programs similar to those used in operational numerical forecasting but adapted to the tropics. To develop such a system, to gain experience of its behaviour and to meet the need for a large number of initial cases from which to select initial and verification analyses, it was decided to run a near-real-time analysis/forecast cycle throughout each of the three phases of GATE using all data available at Bracknell about 24 hours after observation time. The analysis system is described in the paper in this issue by D. E. Jones.

THE FORECASTING MODEL

As indicated above, the model used was a limited-area version of the 11-layer global primitive-equation model recently developed in the Dynamical Climatology Branch. The vertical coordinate is $\sigma \equiv p/p_*$ where p is pressure and p_* is pressure at the earth's surface. The boundaries and nominal central levels of layers are specified in Table I.

TABLE I—LAYER BOUNDARIES AND NOMINAL LEVELS IN σ-COORDINATES

Layer	11	10	9	8	7	6	5	4	3	2	1
Boundaries	1	0·975	0·9	0·79	0·65	0·51	0·37	0·27	0·195	0·125	0·06	0
Nominal level	0·9874	0·9370	0·8438	0·7177	0·5772	0·4363	0·3174	0·2305	0·1574	0·0886	0·0221	

* *Note:* This paper is based on an unpublished report by the quoted authors with some abridgement and further explanations by the Editor.

The vertical resolution was chosen after consideration of representation of the boundary layer, extratropical fronts and jet streams, inflow and outflow of tropical convective systems, and the stratosphere.

In the horizontal, variables were represented on a 2° latitude–longitude mesh with boundary rows along 35°N, 15°S, 77°W and 49°E. The finite-difference scheme was similar to that described by Corby *et alii* (1972), though with modifications in the vertical differencing to maintain energy conservation in the sense discussed by these authors and with time-averaging at every time-step to avoid 'splitting' between alternate forecast fields. Lateral boundary conditions were of the 'sponge' type described by Kesel and Winninghoff (1972). Instead of the non-linear diffusion term described by Corby *et alii* (1972) a filter of the type described by Shapiro (1971) and Francis (1975) was used every six hours to eliminate very short waves from the fields of sea-level pressure, horizontal wind, specific humidity and temperature. The boundary-layer and surface fluxes of heat, moisture and momentum were calculated from the model variables in the lowest three layers and from surface temperature by use of Method I of Clarke (1970). Evaporation was related to potential evaporation and soil moisture in a way similar to that of Manabe (1969), but fixed values of soil moisture were used with a smooth transition over Africa from moist equatorial to dry desert regions. The modelling of convection and large-scale rainfall was similar to that used by Corby *et alii* (1972). A simple radiation scheme was adopted which, however, included diurnal variation of solar heating and climatological values of albedo, specific humidity and cloudiness.

Dynamic initialization

If data obtained from analyses of the fields of wind and geopotential are used as initial data for a primitive-equation model without specific measures to adapt one to the other, high-frequency gravity waves of large amplitude are set up which bear no relation to any meteorological phenomenon and can damage or even obscure the forecast. This is because the wind and pressure fields are not 'balanced' so leading to unrealistic initial accelerations. Harmonization of the fields must be brought about artificially before they can be used to provide realistic forecasts. Various methods of obtaining suitable fields, by what are termed 'initialization procedures', have been proposed. The one applied to GATE data, known as 'dynamic initialization' was due to Nitta (1969). In this the model equations are applied iteratively to damp out the spurious high-frequency modes implied by the analyses.

As both pressure-to-wind and wind-to-pressure adjustments are to be expected among the various vertical modes and horizontal scales of a multi-level model, all the variables were allowed to adjust mutually except that the moisture field was held fixed and all sources and sinks of energy (including latent-heat release) were ignored. This last restriction is rather unsatisfactory—in particular, the balance at low levels should be influenced by friction—but no method has yet successfully incorporated source and sink terms into this type of initialization scheme. One extra effect was, however, introduced: at the end of each cycle a convective adjustment was applied to the temperature fields to prevent the generation of vertical instability.

Tests of the dynamic initialization process showed that external gravity waves implied in the analysed data were successfully removed by applying the

scheme for the equivalent of six hours of model time; indeed two to three hours might well have been enough. Comparison of forecasts made with initialized and uninitialized data showed that surprisingly little damage was done by the presence of spurious gravity waves, at least on a 12- to 24-hour time-scale, although forecasts using initialized data were smoother; rainfall was little affected. The element of balance introduced during the objective analysis may be partly responsible for this.

Forecast procedure

The forecast-analysis cycle was run with 12-hourly updating during Phases I and II of GATE (analyses at 00 and 12 GMT), and with 24-hourly updating during Phase III (analyses at 12 GMT). The change to 24-hourly updating allowed more detailed assessments of the quality of the data and analysis, and of the need for bogus data; it also allowed testing of the forecast over a longer period with less computer usage.

The procedure at time t may be summarized as follows:

(a) A previous forecast provides values of variables on σ-surfaces. Derive values at standard pressure levels by interpolation to provide background fields for analysing new observations made at time t. (This does not apply to relative humidity, which is analysed for σ-layers directly.)

(b) Extract data for time t.

(c) Carry out preliminary analysis. Insert corrections and bogus data as necessary and carry out final analysis.

(d) Interpolate from pressure surfaces to σ-surfaces.

(e) Initialize wind and pressure fields.

(f) Use model equations to advance fields from time t to $t + 12$ or $t + 24$ hours.

The data extracted in step (b) comprised surface and upper-air observations (rawinsonde, radiosonde and pilot balloon) from land stations and ships, aircraft observations of wind and temperature, estimates of wind from satellite cloud photographs, and temperature soundings from satellite radiometers. Numerous difficulties were encountered at first, but most problems had been satisfactorily solved by the time Phase III began.

Results and discussion

Attention will be confined in this section to results of the forecasts carried out during Phase III because these forecasts were made for periods of 24 hours and because data, analysis and modelling had all been improved in the light of the experience gained during the earlier phases.

The large-scale synoptic situation over the area generally varied little during the phase: the Atlantic was dominated by the north and south Atlantic sub-tropical highs with maximum heights in the forecast area of about 24 and 16 dam respectively, while between them a trough with minimum height of about 11 dam linked the continental lows over North Africa and South America. An interesting feature was a simultaneous weakening of northern high and oceanic trough from 8 to 11 September with extremes of only 18–20 dam and

13 dam. In the middle and lower troposphere, troughs moved westwards in the general easterly flow over West Africa and the northern tropical Atlantic. Figures 1 and 2 show 'analysed' and predicted trough movement at $\sigma = 0{\cdot}844$ and 500 mb (where 'analysed' here means 'objectively analysed and initialized') and also positions for 850 mb subjectively estimated from observations at

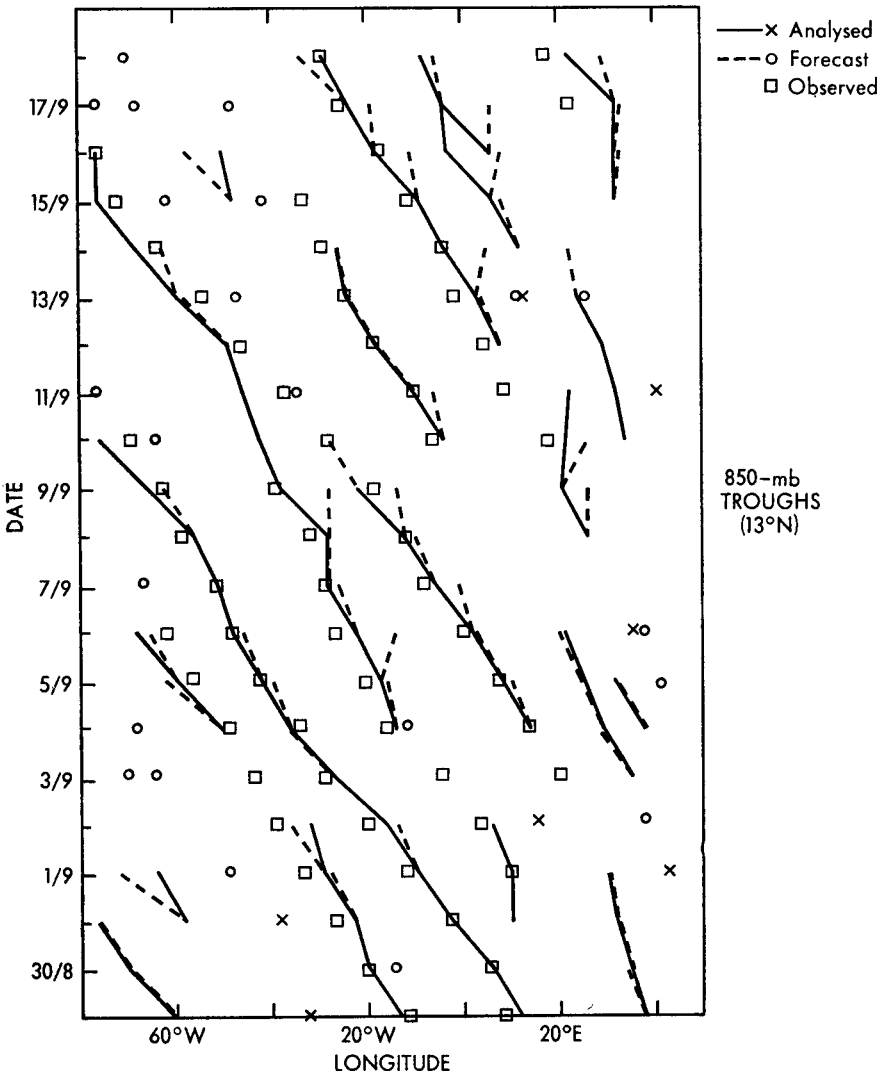

FIGURE 1—TROUGH POSITIONS AT $\sigma = 0{\cdot}844$, 13°N DURING PHASE III OF GATE

x —— analysed positions
o – – predicted positions
Squares mark subjectively estimated 850-mb trough positions.

00 GMT, and occasionally 06 and 18 GMT as well as 12 GMT; where data were inadequate for these subjective estimates, use was made of continuity and cloud information from satellites.

The errors of prediction are summarized in Table II.

The errors at level 9 are large for waves starting over land (20°W–20°E) but

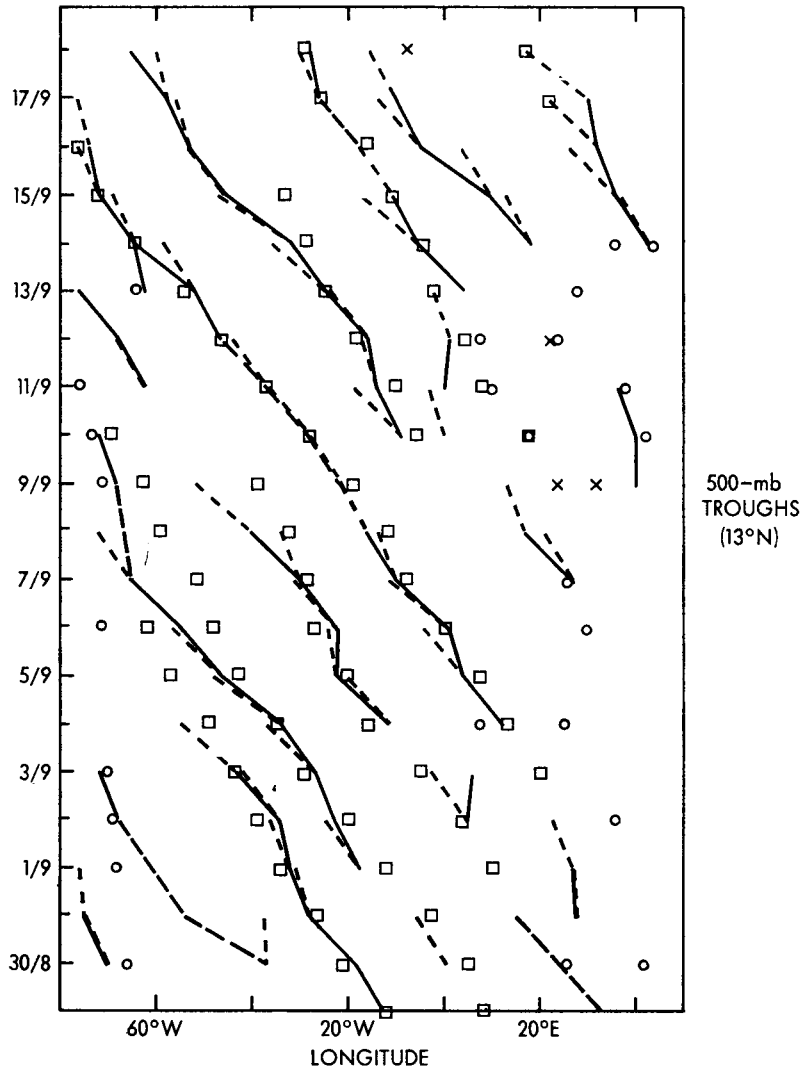

FIGURE 2—TROUGH POSITIONS AT 500 mb, 13°N DURING PHASE III OF GATE

x —— analysed positions
o – – predicted positions
Squares mark subjectively estimated 850-mb trough positions.

are much smaller over the ocean, suggesting that surface and boundary-layer friction and surface heating may have contributed to the error. Errors are much smaller at 500 mb and no longer depend on longitude, probably because of the relatively small effects of convergence and divergence at this level.

TABLE II—MEAN ANALYSED AND PREDICTED 24-HOUR WESTWARD SHIFT OF TROUGHS AND DERIVED ERROR (DEGREES OF LONGITUDE) DURING PHASE III

	60°W–20°W	20°W–20°E
$\sigma = 0{\cdot}844$ (level 9)		
Number of cases	15	18
Analysed motion	6·3°	6·3°
Forecast motion	5·3°	2·1°
Error	−1·0°	−4·2°
500 millibars		
Number of cases	20	16
Analysed motion	6·9°	6·5°
Forecast motion	7·1°	7·4°
Error	+0·2°	+0·9°

The quality of the rainfall forecasts may be judged on the broad scale from Figure 3 which shows isohyets drawn from observed and forecast totals for the period from 4 to 14 September. The observed distribution was calculated from 06 GMT observations and the forecast from the totals for the 24 hours to 12 GMT; the area from 5°N to 20°N and from 10°E to 20°W was divided into 5° squares, the 24-hour totals (observed and forecast) were meaned for each square and the isohyets were drawn on the basis of these areal mean totals.

Most of the observed and forecast rain occurred in the strip from 5°N to 10°N, and Figure 4 shows the distribution with respect to longitude and time of the 24-hour rainfall totals in this strip, both observed and forecast. The figure shows that the model successfully produced the alternation of wet and dry periods together with roughly correct longitudes for the rainfall maxima. Each wet period was associated with a westward-moving wave or trough; somewhat similar relationships were observed using larger samples of data by Carlson (1969) and Burpee (1974). (It is of interest that the wave of 5–8 September developed into hurricane 'Fifi' which devastated Honduras a few days later.)

On the fine scale, large spurious amounts of rain were forecast at a few grid points, particularly over central Africa. One reason for this was the occurrence of spurious thickness maxima produced by faulty analysis in regions where data were sparse; these spurious maxima tended to generate intense vortical disturbances. The method of parameterizing convection may also have contributed since improved results were subsequently obtained with a new 'parameterization' scheme.

An important measure of the quality of any numerical forecasting method is the degree to which it systematically reproduces the mean structure of the real atmosphere. Discrepancies between forecast and actual mean structures also provide good clues to deficiencies in parameterization and computational method which would cause major faults in longer 'climatic' simulations.

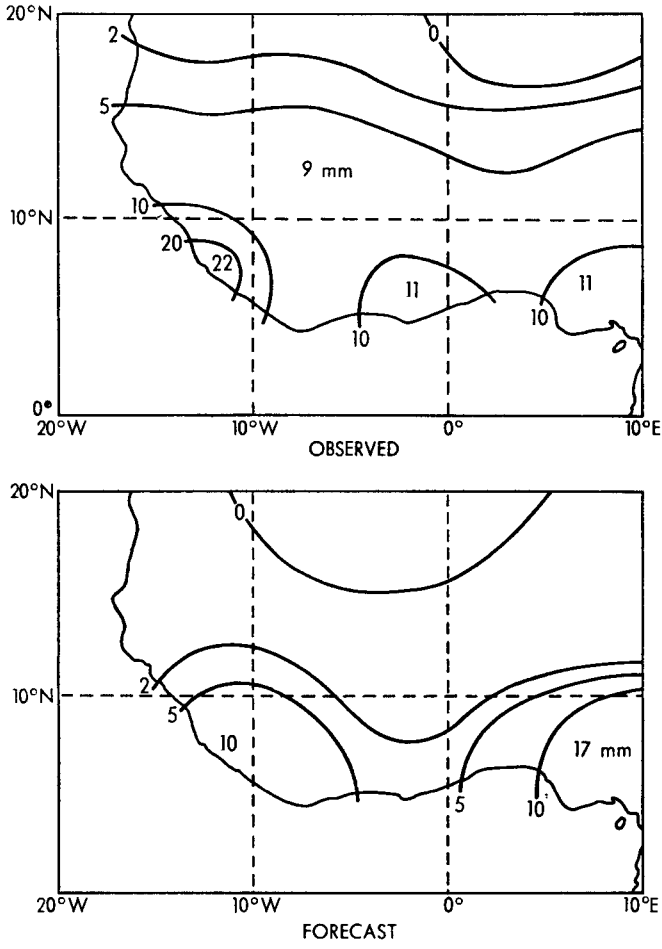

FIGURE 3—MEAN 24-HOUR RAINFALL TOTALS FOR THE 10-DAY PERIOD 4–14 SEPTEMBER 1974

Examples are presented here of the average forecast 24-hour change in the thermal structure of the atmosphere as illustrated by mean vertical cross-sections along certain longitudes. Time-mean fields were constructed by taking a mean of the initial conditions for 9–14 September and a mean of the 24-hour forecast fields verifying on 10–15 September. To show the structure of the temperature fields more clearly, temperatures were expressed as differences from those in a typical model atmosphere meaned along 7°N.

Figures 5 and 6 show the vertical cross-sections of the forecast temperature changes along 23°W and 3°E. The most noticeable feature, common to both, is the warming that takes place in the lowest layer during the forecast. Over desert regions, north of 13°N at 3°E surface temperatures increase by about 5 K during the forecast; this is probably due to the simplified treatment of radiation and soil-moisture content.

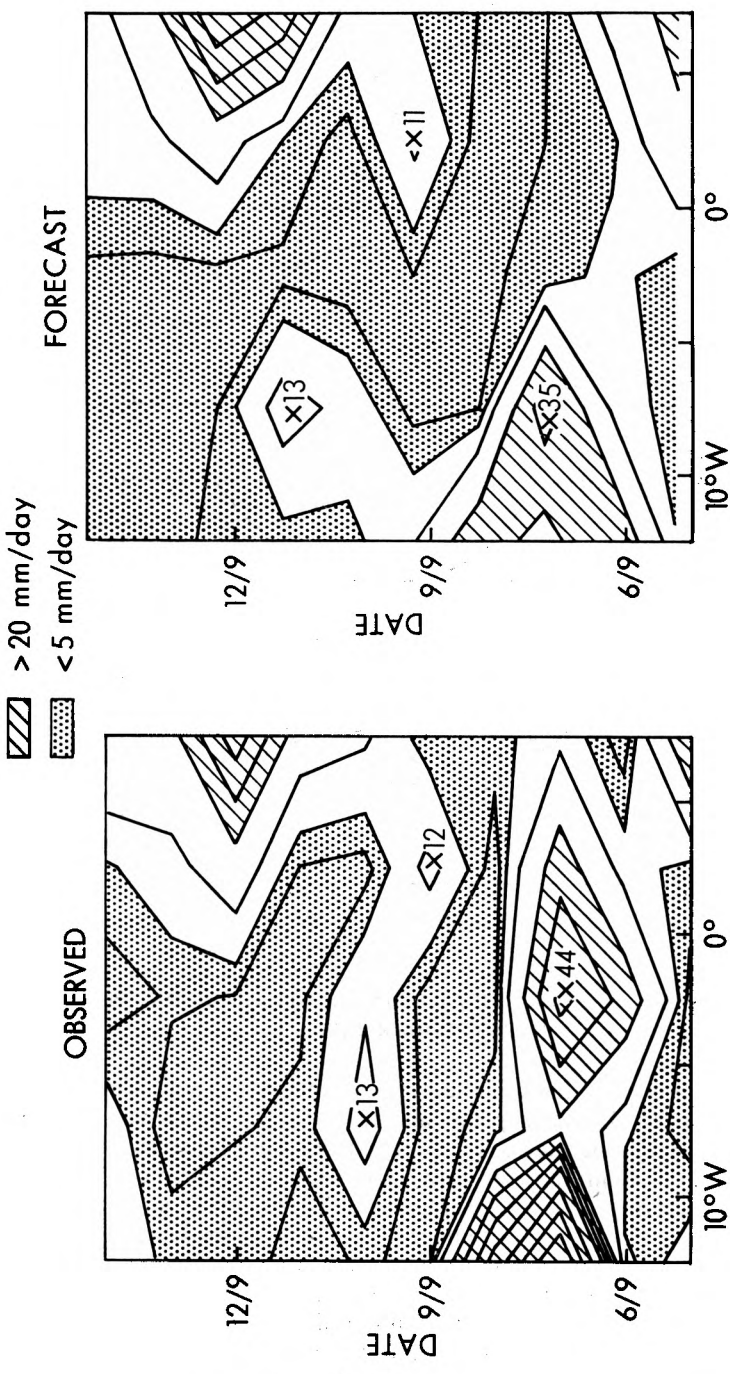

FIGURE 4—MEAN TOTALS OF OBSERVED AND FORECAST RAINFALL FOR PREVIOUS 24 HOURS

Rainfall totals are expressed in millimetres. Isopleths are at 2, 5, 10, 20, . . . 80 mm/day.

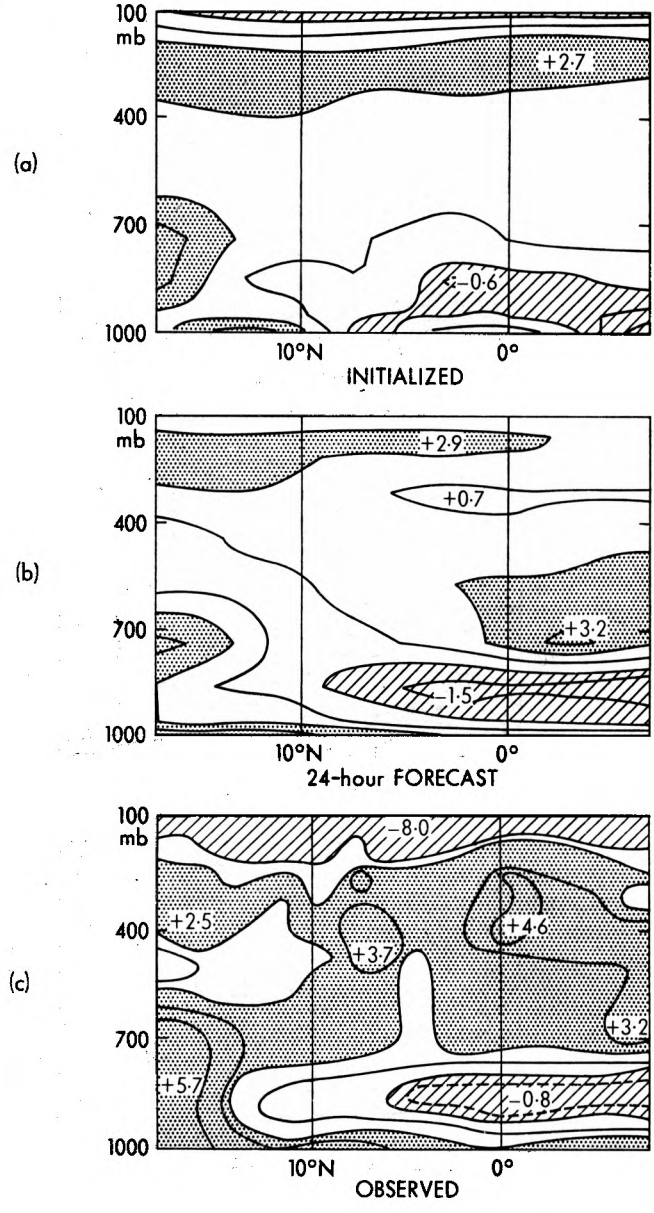

FIGURE 5—VERTICAL CROSS-SECTIONS OF TEMPERATURES IN KELVINS ALONG 23°W

Time averages for 9–14 September 1974 at 12 GMT expressed as departures from model's 7°N mean. Isopleth interval 1 K; values >2 K stippled, <0 K hatched.
(a) Initialized (9th–14th); (b) Forecast (10th–15th); (c) Observed (9th–14th).

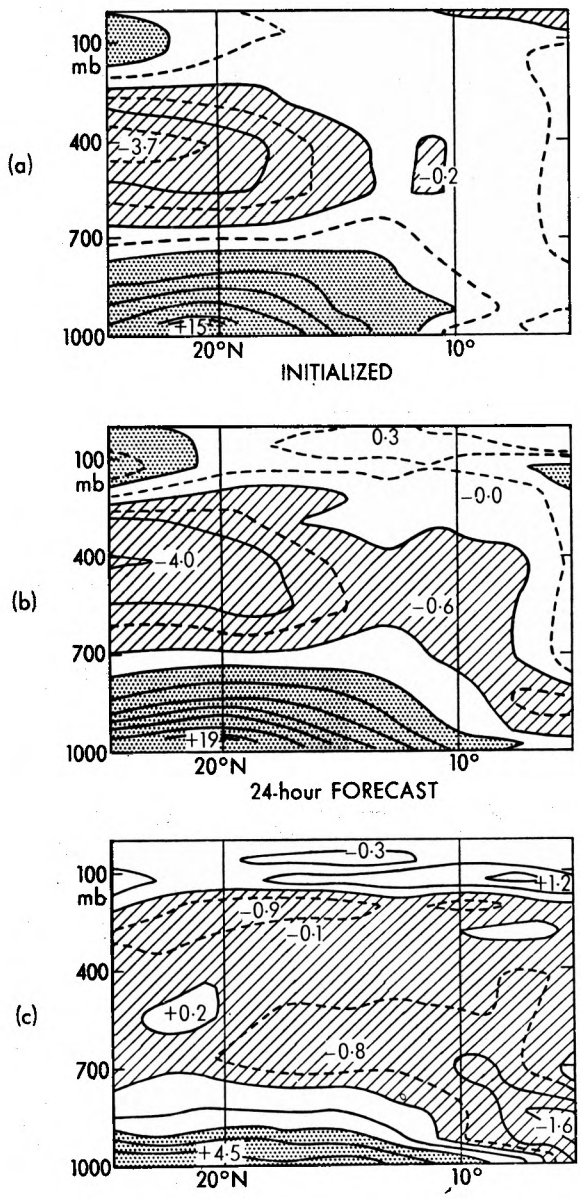

FIGURE 6—VERTICAL CROSS-SECTIONS OF TEMPERATURES IN KELVINS ALONG 3°E

As Figure 5, except that isopleth interval is generally 2 K in (a) and (b).
(a) Initialized; (b) Forecast; (c) Forecast minus Initialized.

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PLATE I—THE ENTRANCE TO THE GATE OPERATIONS CONTROL CENTRE (GOCC) IN DAKAR

C.C.O.E. is derived from 'Centre de Contrôle des Opérations de l'ETGA'.

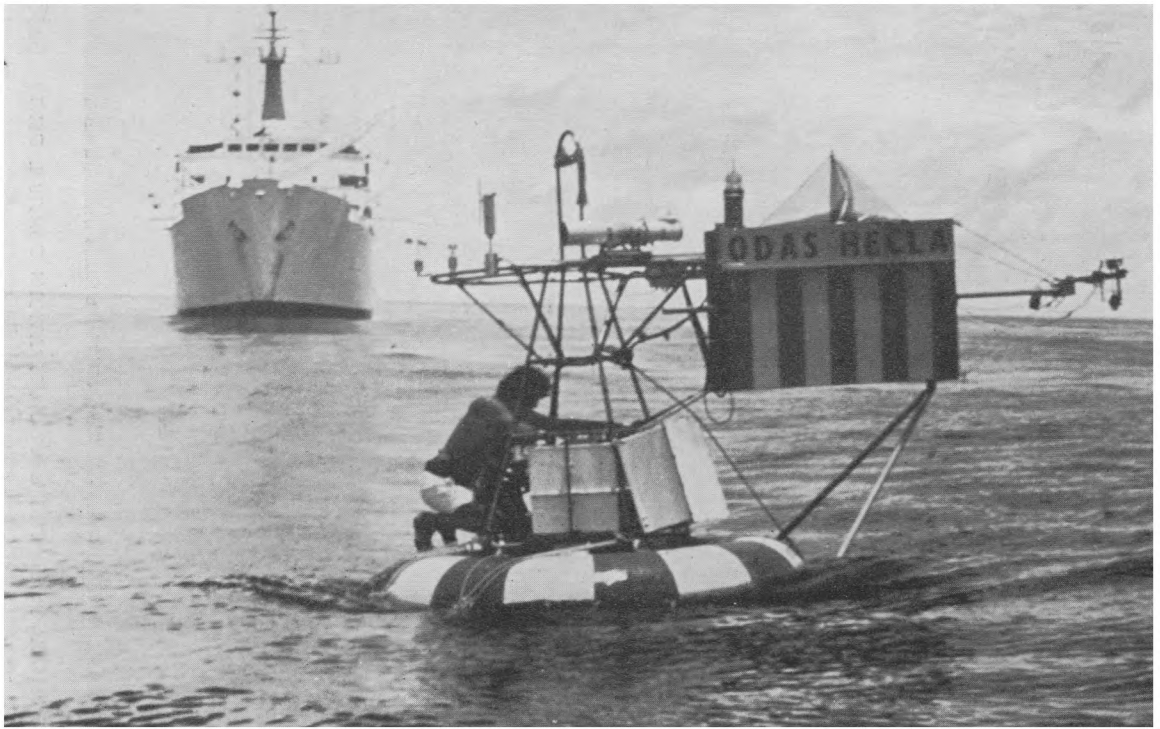

PLATE II—MAINTENANCE DURING NEARLY CALM CONDITIONS OF THE METEOROLOGICAL BUOY LAUNCHED FROM H.M.S. *Hecla* The *Hecla* is in the background (see page 275).

PLATE III—M.V. *Charterer* AT ANCHOR AT DAKAR

Soviet oceanographic ships are visible in the background. (See page 284.)

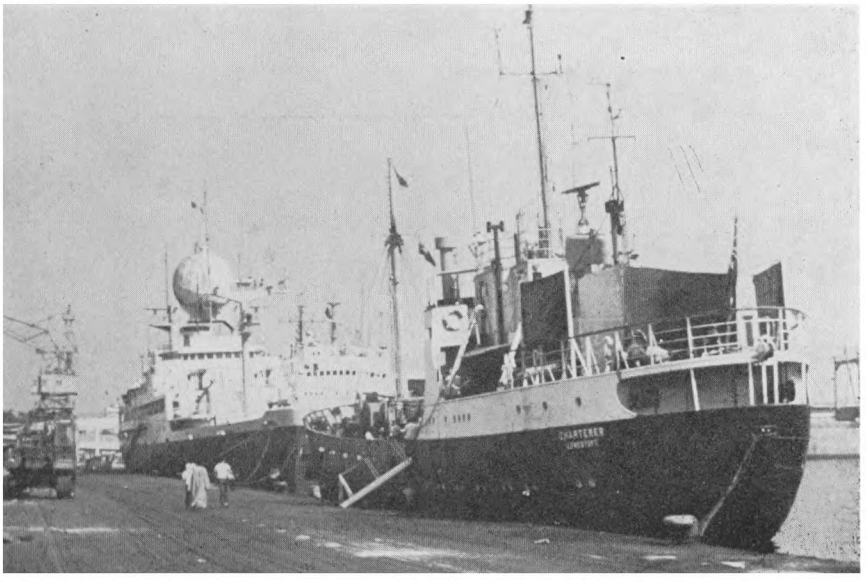

PLATE IV—m.v. *Charterer* (FOREGROUND) AND THE CANADIAN RESEARCH VESSEL *Quadra*

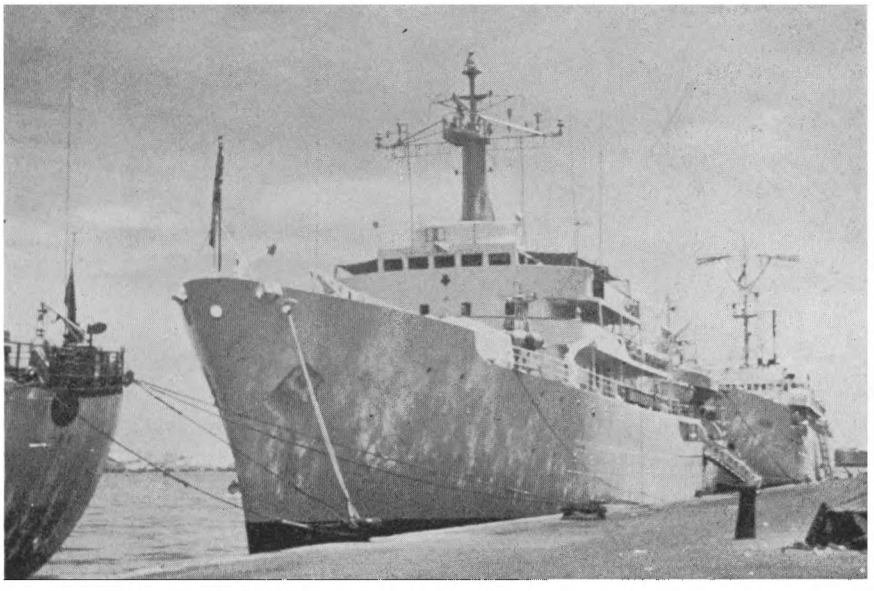

PLATE V—H.M.S. *Hecla* AT DAKAR WITH A SOVIET SHIP IN THE BACKGROUND
(See page 272.)

During the forecast, at 23°W and south of 7°N, an inversion forms below level $\sigma = 0{\cdot}718$ owing to warming at that level and cooling at $\sigma = 0{\cdot}844$. This is not an unrealistic structure and is often observed over tropical oceans in areas where there are few disturbances. A vertical cross-section of time-meaned observed and subjectively analysed temperatures along 23°W has also been constructed for comparison with the analysed and forecast structures (Figure 5 (*c*)), and this clearly shows an inversion between 900 and 700 mb. It seems that this feature, the warm surface layer and the probably spurious detail in the observed middle and upper troposphere are smoothed out in the analysis and interpolation to σ-levels. The forecast re-creates the inversion and also the warm layer near the ocean surface. The large negative departures of the observed temperatures near 100 mb from the model's 7°N average are at the tropopause which cannot be represented in this detail with the model's layered structure. A general cooling of about 1 K in the middle troposphere of the initialized field relative to the observed can probably be explained by a correction for estimated ship sonde error of about −0·5 K and the cooling evident in the 24-hour forecasts (Figure 5 (b)) which were used as background for the analysis. This forecast cooling appears to be due to insufficient compensation of radiative cooling by convective heating.

Cross-sections for relative humidity (not shown) suggest that the model had a tendency to make the air too moist. The form of convective parameterization used apparently required the whole grid square to be too near saturation before giving precipitation; this may partly account for the rather low values of predicted rainfall north of 10°N (Figure 3).

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METEOROLOGICAL OBSERVATIONS FROM H.M.S. 'HECLA' DURING THE FINAL PHASE OF GATE

By N. THOMPSON

(Meteorology Division, Chemical Defence Establishment, Porton Down)

SUMMARY

A description is given of tethered-balloon observations from H.M.S. *Hecla* during the third phase of GATE and of observations from an adjacent meteorological buoy. Some results obtained during the passage of a weak line-squall are discussed.

INTRODUCTION

An intensive study of the atmospheric boundary layer was made during the final phase of GATE by a number of well-equipped ships which took up positions in the C-scale array located within the B-scale polygon (Figure 1). Most of these ships were able to measure the low-level wind profile with fair accuracy, using pilot balloons tracked by stabilized radar or optically, and most also had tethered-balloon systems making multi-level measurements of wind, temperature and humidity, at heights up to about 1000 m. A number of ships also made surface observations with high time-resolution and accuracy, using sensors mounted on booms extended in front of the ships or on adjacent buoys.

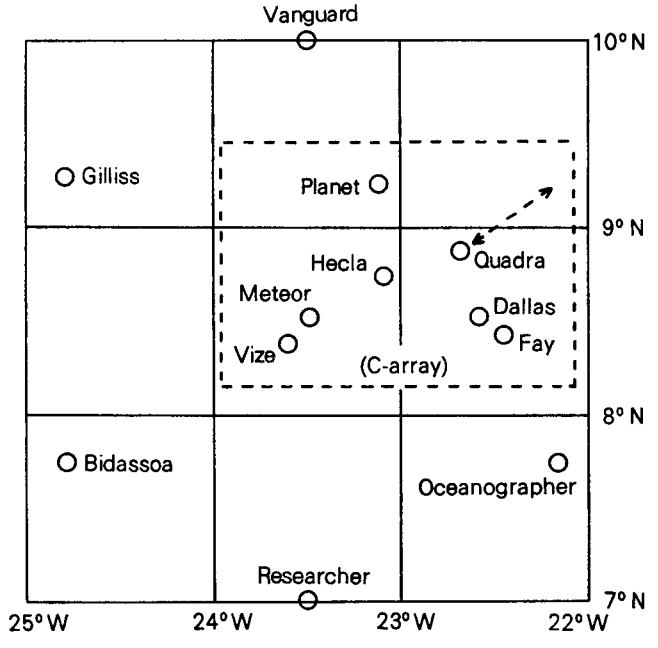

FIGURE 1—POSITIONS OF B- AND C-SCALE SHIPS IN PHASE III (30 AUGUST–19 SEPTEMBER 1974)

H.M.S. *Hecla* at the centre of the array carried teams from Imperial College and the Meteorological Office (Porton) who were concerned with a variety of boundary-layer observations. The contribution of the Imperial College group will not be discussed in this note; it included low-level windfinding using a very accurate stabilized radar system, radiosonde observations and all-sky cloud photography.

The main components of the program of the Porton team were the investigation of turbulence structures in the lowest few hundred metres of the atmosphere using a tethered-balloon system, and the measurement of near-surface parameters such as wind and temperature by a meteorological buoy (see Plate II). Balloon and buoy measurements had been made from the *Hecla* during the Joint Air–Sea Interaction Experiment (JASIN) in 1970 (Thompson, 1972) but the GATE equipment incorporated a considerable number of modifications. The remainder of this note describes the aims and experimental details of the program and gives a brief assessment of the results to date.

Tethered-balloon measurements

Previous experience had shown that the tethered-balloon system adopted would not allow multi-level measurements at heights up to much more than 400 m and the objectives of this program were necessarily restricted to the investigation of turbulence structure in the sub-cloud layer. Other constraints were the inability to fly in rain for long periods without damage to equipment or on occasions with adjacent lightning activity, or to obtain satisfactory data in very light winds. Within these limitations the program set out to acquire over as wide a range of conditions as possible multi-level data on wind velocity, temperature and humidity from which could be deduced, *inter alia*, the vertical fluxes of heat, moisture and momentum and the relation of these and other turbulence statistics to the large-scale flow fields and local cloud organization. Analysis of the results depends therefore on the use of cloud photographs, radiosonde data and, for example, divergence data.

The balloon (volume 80 m^3) was of conventional construction with air-filled fins; an air-filled compartment of variable volume under the helium cavity allowed compensation to some extent for expansion or contraction of gas due to temperature or height variations. After initial inflation on deck any further topping-up was through an umbilical cord about 20 m long which ran down the side of the tethering cable. The steel cable with a tensile strength of 1000 kg was paid out or recovered by a variable-speed electric winch on the forward end of the *Hecla*'s flight deck. Between the winch and snatch-block tether aft was an 'accumulator' consisting of fixed and movable pulleys whose spacing was controlled by a hydraulic ram; the cable was led round the pulleys and the stroke and speed of the ram were governed by a suitably integrated signal from a vertically stabilized accelerometer unit, thus compensating for motion of the tethering point of the cable (the snatch block aft) by continuously adjusting the amount of cable paid out beyond the accumulator. The balloon and tether were designed to survive winds of at least 25 m/s but were not put to this test since the maximum winds experienced were little more than 15 m/s.

The turbulence measurements were made with one or two instruments attached to the balloon cable at heights up to about 400 m. The measured parameters were magnitude of wind vector (miniature cup anemometer with horizontal rotor axis), inclination of airflow to the horizontal (hot wires mounted

on a pendulum), air temperature and wet-bulb depression (fine dry and wet platinum wires). Sensors were mounted on a light vane (Figure 2) that pivoted about the balloon cable; signal-conditioning circuits and transmitter were in a separate box attached independently to the cable below the vane. Signals were converted to audio frequencies and transmitted to the ship via 380-MHz links. Data were recorded on a multi-track analogue tape recorder in the ship's dry laboratory and then monitored 'off tape' and displayed on an ultra-violet recorder after de-multiplexing. Inclinometer and temperature circuits were calibrated before each run by substitution of dummy sensors (resistances). Variable offset resistances were incorporated in the airborne system in order to achieve maximum resolution in the temperature measurements: typical full-scale ranges were ± 2 deg. The expected accuracy was about $\pm 0{\cdot}2$ deg for wet- and dry-bulb temperatures and 5 per cent for inclination and wind speed. Rechargeable batteries used in the airborne system allowed runs of about 10 hours' length before battery changes were required.

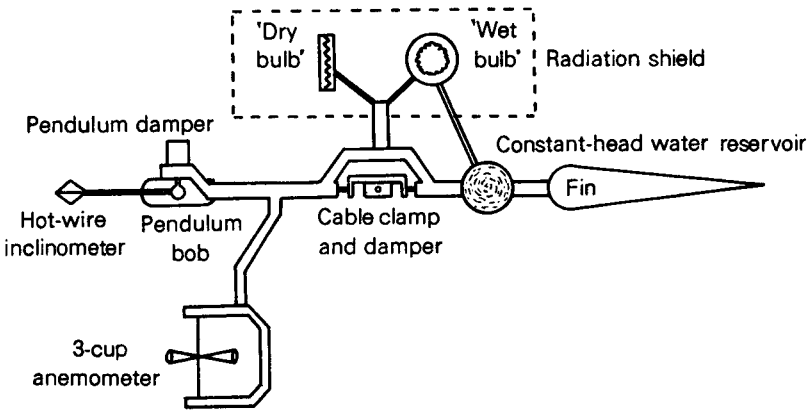

FIGURE 2—PLAN VIEW OF TURBULENCE SENSORS MOUNTED ON VANE

Overall length of vane is 0·7 m.

The balloon was inflated on 29 August but was found to lose its symmetry whenever not highly inflated (for example when the helium contracted in the evening owing to radiational cooling) and this resulted in rather unstable flying characteristics. After an early incident in which the balloon was driven to near the surface in a squall the gas was transferred on 31 August to another balloon which performed satisfactorily for the remainder of the experiment. Mechanical damage was caused to the instruments on two occasions by violent turbulence near the ship when being hauled down and on another occasion by a ship's power failure which caused a severe snatch in the cable accumulator and large downward acceleration of the cable. The accumulator system was out of action for maintenance for about 15 per cent of the time but otherwise performed satisfactorily and produced a significant reduction in sensor movement caused by ship's motion. There were occasional breakages of the fragile sensors and some electronic faults but sufficient replacements were carried to avoid all but temporary suspension of the measurement programs.

Apart from occasions with very light wind or heavy rain and lightning activity the most serious curtailment of the program was caused by adjacent low-flying aircraft. Aircraft missions were flown in the C-scale area on many days and since the *Hecla* had no aircraft navigation aid such as DME (Distance Measuring Equipment) the result was that the balloon had to be hauled down to about 50 m (too low to make measurements) on nearly all these occasions. On a few occasions with good weather conditions the balloon was allowed to be raised after an hour or so with aircraft in the vicinity but on nearly half the days there was a break of about six hours due to aircraft activities.

Two hundred hours of data were obtained, mostly with two heights of measurement. Meteorological conditions sampled ranged from highly suppressed (dry) convection to weak line-squalls with heavy rain and while some of the data suffered from instrumental faults it is expected that most will produce useful results. However, the analysis has been complicated by the fact that the *Hecla* was not anchored during GATE and made numerous changes of speed and course, often in association with its oceanographic (STD) program. This introduced difficulties in spectral analysis of the tethered-balloon data and makes it necessary to correct wind-speed data with the help of 1-minute values of heading and speed printed out by the ship's computer.

Buoy measurements

In strong sunshine (or at night with clear skies) and relatively light winds it is difficult to make representative temperature measurements from a ship with conventionally mounted instruments and at all times the corresponding wind measurements suffer from the ship's influence on the airflow. A meteorological buoy was used in an attempt to overcome these difficulties. The basic structure was a toroid of diameter 2·5 m with a lattice superstructure. The buoy was anchored in about 4700 m of water, 300 m of anti-fish-bite wire with braided nylon below being used. Wind speed was measured by a small reed-switch cup anemometer with built-in ratemeter giving a voltage output proportional to wind speed. The wind vane was a self-referencing type with built-in compass, and produced a single voltage output proportional to direction. Temperature sensors were platinum resistance thermometers connected to Wheatstone bridges and measuring air temperature, wet-bulb depression and sea–air temperature difference. The sea thermometer was at a depth of 1 m and other sensors were mounted at a height of 2 m on the upwind side of the superstructure. The air thermometers were mechanically ventilated inside a tubular radiation shield. The pressure sensor was a KDG aneroid connected to a Meteorological Office static head mounted near the other sensors. A large fin was used to orientate the buoy into wind. Data were recorded on a Rapco digital logger at 5-minute intervals and on a Plessey Logger at half this rate. Timing pulses for both systems came from the Rapco clock.

The buoy was visited on most days for washing the wet-bulb thermometer, changing batteries and checking on logger operation, and appeared to perform satisfactorily for about the first half of the measurement program, apart from intermittent operation of the thermometer aspirator (a fault eventually rectified). The timing system then failed following breakdown of the Rapco logger but logging restarted after a break of about three days, using a ¼-hourly mechanical timer in the Plessey Logger. On replaying the data tape it was found that both

the wet-bulb depression and air–sea temperature-difference signals had failed at the time when the buoy was launched, apparently because of damage to electrical cables caused by the launch. Fortunately the quantities which were to be derived from them (specific humidity and sea temperature) are those which can be obtained with fair accuracy from a ship by using an Assman psychrometer and bucket thermometer (both of which were used on board the *Hecla*). (See Plate II.)

Other measurements

Net all-wave radiometers (Kew-pattern ventilated fluxplates) were mounted on booms extending 6 m beyond the ship's sides to port and starboard. Outputs were logged on a potentiometric recorder. A static-pressure head (Meteorological Office pattern) was mounted on a boom to starboard of the mainmast and connected to two precision aneroid barometers mounted close to sea level in the gyroscope room. A small anemometer and wind vane were placed by the side of the static head and connected to the potentiometric recorder; the data were used in conjunction with the computer log of ship heading and speed to derive 1-minute values of wind velocity.

Intercomparisons

The buoy was lifted on 16 September and the *Hecla* then steamed to a position close to the *Meteor* in order to intercompare all upper-air and surface systems. The buoy was relaunched and tethered to the *Meteor*'s buoy for a period of about 15 hours. Both ships flew their tethered balloons for several hours with instruments at heights of 200 and 400 m. Low-level windfindings were compared by simultaneous radar tracking from both ships of pilot balloons. Standard meteorological observations were carried out at quarter-hourly intervals. The *Hecla* returned to station on 17 September.

Data processing

The tethered-balloon data were digitized at 10 Hz at Porton and then converted to horizontal and vertical wind speed, temperature and specific humidity, and transcribed to archive tapes using the Bracknell 360/195 computer. These archive tapes form the basic data set from which all results will be obtained. At present this data set is being used to produce various mean values and derived quantities such as standard deviations and covariances which are required by the World Data Centres in Russia and the USA, and the GATE Boundary Layer Sub-program Data Centre in Hamburg: vertical fluxes of heat, water vapour and momentum are also being calculated, and by the time this note is published it is expected that spectra and cospectra of the four parameters calculated at each height will have been produced from some of the data.

Other data such as those from the buoy are punched on cards and then archived on tape at Bracknell prior to international exchange.

Discussion

An extended discussion is inappropriate at present (July 1975) because of the considerable amount of data processing needed before the final results can be

obtained. First results are very encouraging and demonstrate that our participation in GATE was a success. To conclude this note and in order to indicate the sort of data obtained by the balloon system a brief description is given below of observations made before and during the passage of a weak line-squall.

On 13 September there was widespread moderate convection with a fair number of showers falling from large cumulus, and also some much larger cumulonimbus. The amount of convection suggested that the average low-level flow over the area was convergent. The general surface flow was south-westerly, about 8 m/s, and the upper flow which was approximately easterly was bringing over the ship anvils from thunderstorms some 30 km away to the east. After about 0900 GMT one of the larger cumulus clouds on the starboard forward quarter began to develop quickly vertically and then laterally and soon there was a line of showers orientated roughly north–south associated with it. The line then approached the ship, intensifying and deepening to become an obvious line-squall. The main rain areas passed on either side of the ship but the precipitation there was still fairly heavy during a period of about 20 minutes starting at about 1041. The rain lasted about an hour in all. The tethered-balloon system was flying with instruments at heights of approximately 96 m and 280 m while the squall developed and measurements were continued until shortly after 1100 GMT when a haul-down was necessary because of an impending aircraft mission.

Parameters derived from the tethered-balloon data for the period from 1000 GMT to the end of recording are plotted in Figure 3. Winds were around 9 m/s initially with a small increase with height. At the upper level the speed increased steadily after 1020 GMT until the squall reached the ship but at the lower height this increase was delayed until about 1030. Before the squall's arrival temperature fluctuations were small at both levels, probably because of the small air–sea temperature difference ($\approx 0{\cdot}5$ deg), but at the lower level in particular the variations of specific humidity were more marked. Vertical velocity fluctuations were very small at 280 m but much more pronounced nearer the surface where they are seen to be well correlated with fluctuations of water vapour.

The data were used to obtain vertical fluxes of sensible and latent heat by eddy correlation over the period 1000–1036 GMT and the results are plotted against height in Figure 4. The surface estimates were obtained by using bulk aerodynamic relations with values for the transfer coefficients for sensible and latent heat of 2×10^{-3} and $1{\cdot}3 \times 10^{-3}$ respectively (Muller-Glewe and Hinzpeter, 1975; Dunckel *et alii*, 1974).

The striking feature of the Figure is the strong convergence of the water-vapour flux. It is possible that the shortness of the length of record used has resulted in the loss of significant low-frequency contributions to the fluxes at the upper levels (the lowest resolved frequency was about 10^{-3} Hz) but the convergence is probably genuine in view of the small fluctuations of vertical velocity at the upper level: if unchanged it would lead to near-saturation in the layer up to 280 m in a few hours. In fair-weather trade-wind conditions it has been found (e.g. Donelan and Miyake, 1973) that the rate of decrease with height of the water-vapour flux is small and the present results suggest therefore that the boundary-layer structure was being or had been modified considerably by large convective systems in the vicinity.

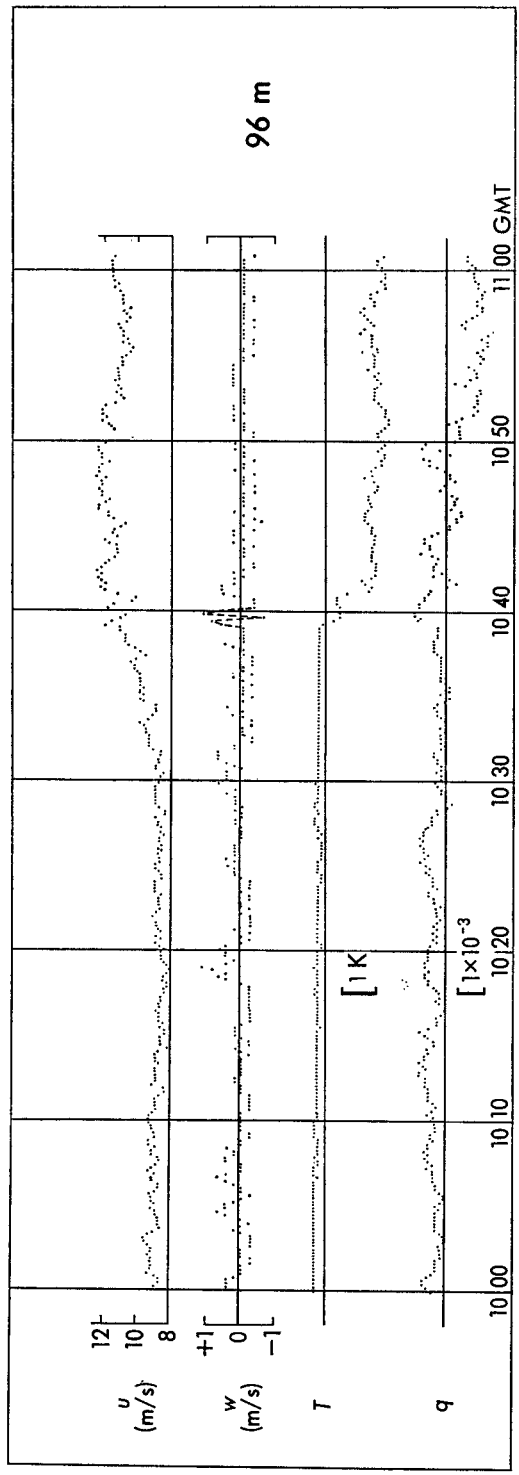

FIGURE 3—VARIATIONS OF WIND, AIR TEMPERATURE AND SPECIFIC HUMIDITY RECORDED ON 13 SEPTEMBER 1974 AT A HEIGHT OF 96 METRES

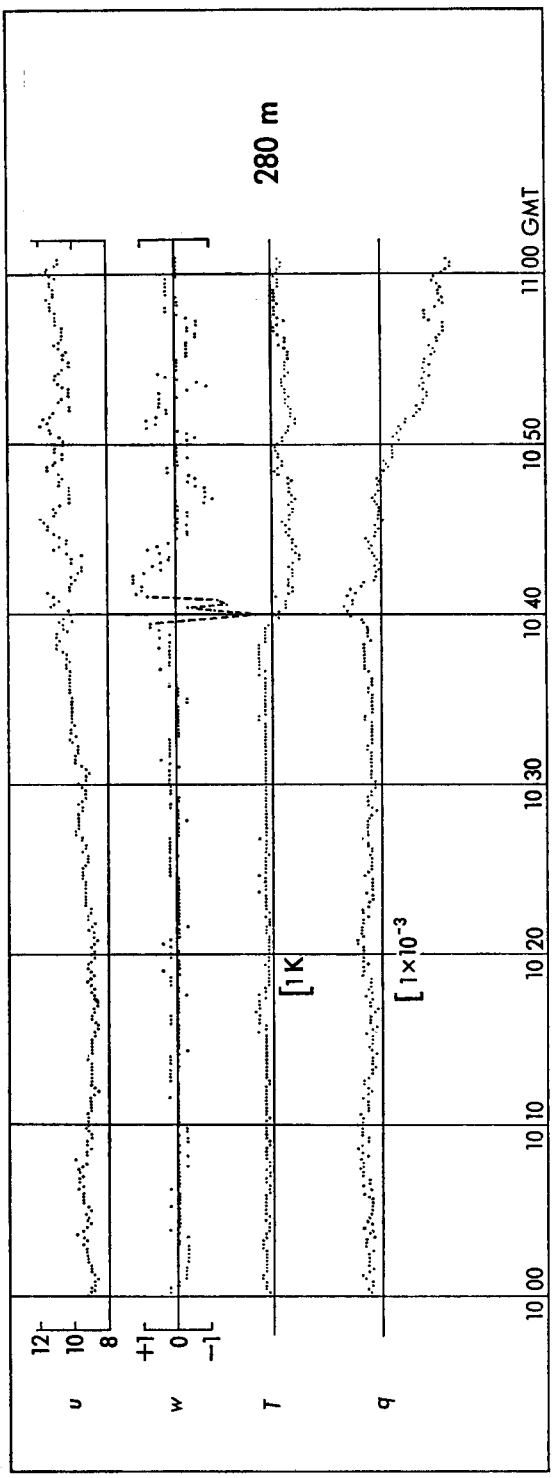

FIGURE 3 *continued*—VARIATIONS OF WIND, AIR TEMPERATURE AND SPECIFIC HUMIDITY RECORDED ON 13 SEPTEMBER 1974 AT A HEIGHT OF 280 METRES

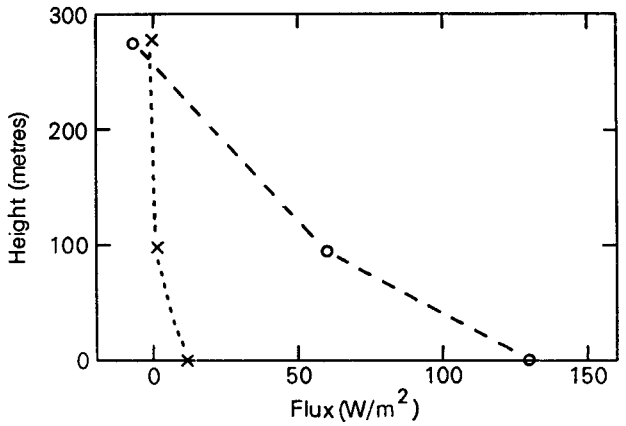

FIGURE 4—VERTICAL HEAT FLUXES 1000–1036 GMT, 13 SEPTEMBER 1974

x - - - x Sensible heat o – – o Latent heat

The surface wind backed slightly (from 225° to 210°) a few minutes before arrival of the squall, began to increase significantly after about 1037 GMT, and veered temporarily to 270° and increased further just before the start of the rain. The line was orientated roughly from 020° to 200° and the wind component perpendicular to the line increased from about 2 m/s to 7 m/s during its passage between 1038 and 1041 GMT. Successive radar pictures suggested a speed of propagation of about 5 m/s (or 900 m in 3 minutes) and the corresponding divergence was therefore about -5×10^{-3}. It was not possible to calculate divergence from the tethered-balloon measurements in the absence of wind-direction data, but at 280 m the divergence was almost certainly numerically smaller than that at the surface because of the smaller change of wind speed on passage of the squall. After about 1110 GMT the surface wind had decreased to near 8 m/s, little different from its value before the arrival of the squall.

The squall's arrival was marked by a rapid fall of temperature at the surface and the two tethered-balloon levels (Figure 3) and a brief increase in specific humidity. The air then became drier and by 1100 the specific humidity at 280 m was about 3×10^{-3} lower than initially, with about half this decrease at 96 m but little change at the surface. The largest fall of temperature was at the surface, about 2·5 K, with the least change at 280 m. The vertical-velocity fluctuations became considerably larger at the upper level when the squall arrived and on average there were updraughts at both heights for a few minutes after temperatures began to decrease but later the average motion was downward. The differential fall of temperature produced a strongly stable layer away from the surface, especially between 96 m and 280 m and this seems to have inhibited vertical-velocity fluctuations at the lower of these two levels but at 300 m where the stability changes may have been smaller the level of turbulence remained high.

Both tethered-balloon levels experienced a double downdraught superimposed on the generally rising motion in the squall-line's vicinity. The downdraughts were delayed by about 25 seconds at the upper level and allowing for the angle of the balloon cable this implies a backward slope of the undercutting cold air of around 10 degrees, but this value is very sensitive to the

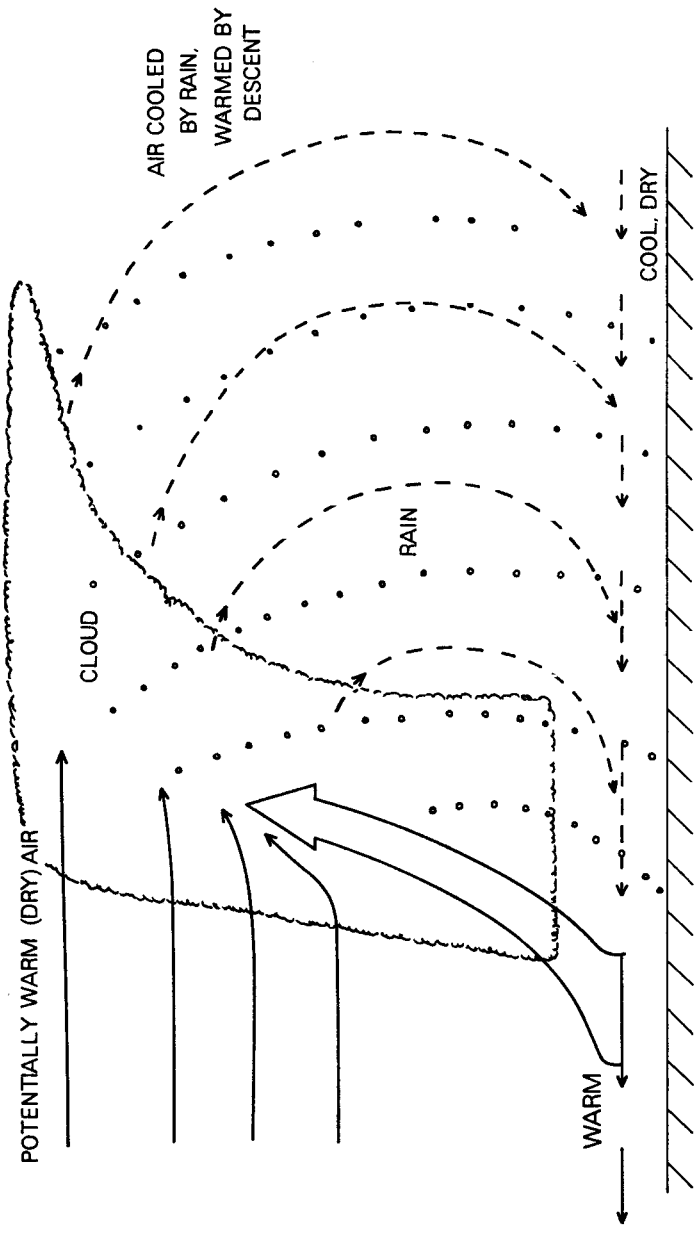

FIGURE 5—SIMPLIFIED CROSS-SECTION OF LINE-SQUALL

speed of travel of the squall which was known only approximately. The mean upward velocity at the upper level over the period from 1038 to 1046 GMT was 0·25 m/s and at the lower level (1038–1042) 0·15 m/s. Assuming that the divergence was close to zero apart from a 3-minute period centred close to 1040, and that it was constant with height, the calculated vertical velocities are 0·7 and 0·4 m/s respectively. If the divergence decreased linearly to zero at 280 m the calculated values become 0·35 and 0·3 m/s, still significant overestimates.

In general the data support the classical picture of the line-squall maintaining itself through wind shear and evaporative cooling (Figure 5). Air behind and within the squall must have been cooled by evaporation of rain into it and since even then it is drier than the air originally at the same height it must therefore have originated at higher levels. There are no representative radiosonde data for the period from which the temperature and humidity data above the surface can be deduced (a sonde was released from the *Hecla* at 1102 GMT but this ascended through the main rain area) so it is not possible to draw any firm conclusions about the level from which the dry air at 280 m originated. However, rough calculations based on the average of radiosonde ascents made from Russian ships in the A/B array in Phase III (Antsipovich *et alii*, 1975) suggest that the air descended from a level near 1500 m if it is assumed that insignificant mixing with air at lower levels took place. The vertical wind shear separated the updraught and downdraught regions and allowed the latter to develop over a wide area. The surface fluxes were estimated from the ship's surface data by using the bulk aerodynamic formulae. The sensible heat flux increased by a factor of about 8 on arrival of the squall, and the Bowen ratio changed from 0·08 to 0·5, with a doubling of the total heat flux (sensible plus latent heat) to about 290 W/m^2. The squall therefore appears to be a successful mechanism for producing enhanced vertical transfers, first by removing moist lower-boundary-layer air from an area of some tens of square kilometres, pumping it upwards and replacing it with dry air, and secondly by enhancing the surface fluxes themselves.

ACKNOWLEDGEMENTS

The use of the facilities provided by H.M.S. *Hecla* was by permission of the Hydrographer of the Navy. Many others gave assistance and advice, particularly the ship's company of the *Hecla*, Lt Cdr T. McAndrew, and D. Winters, D. R. Davies and J. Whitlock, who took part in GATE and were involved in many aspects of instrumentation and data processing.

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551.506.24 : 551.507.25

THE METEOROLOGICAL OFFICE CONTRIBUTION TO THE SHIPBORNE OPERATION OF GATE

By P. H. JEFFRIES

(Lerwick Observatory)

SUMMARY

The ships chartered by the Meteorological Office as part of the UK contribution to GATE are described together with an account of the instruments carried and observations made; these included wind, pressure, sea temperature, radiation, rainfall, and six-hourly upper-air soundings. Aerosol sampling was also carried out as part of an investigation into the transport of Saharan dust. Some practical difficulties are described and a summary given of the results obtained.

INTRODUCTION

GATE (GARP Atlantic Tropical Experiment) took place during the summer of 1974. It was a unique, major international operation planned to examine the many factors which control the interaction of sea and air over the tropical North Atlantic. It is the redistribution of the excess solar energy received in the tropics towards the polar regions which produces the weather systems of the middle latitudes. An appropriately detailed knowledge of the tropical atmosphere is, therefore, a prerequisite to a better understanding of the massive heat engine which is the earth's atmosphere.

The Experiment took place in three phases broadly covering July, August and September. This is the time when solar heating is at its maximum, the Intertropical Convergence Zone (the ITCZ) has moved northwards following the sun, and certain recognizable features show their maximum frequency. One of these recurring features, known as a cloud cluster, has been revealed during satellite surveillance of the tropics. Such clusters are typically about 100 kilometres in diameter. During their passage westwards across the Atlantic they sometimes disperse or, at the other extreme, develop into the hurricanes which are features of the west Atlantic and Caribbean Sea.

To examine the processes in detail throughout the GATE area (20°N to 10°S and 40°E to 70°W) was impossible. In planning the Experiment, interest was concentrated in an area most likely to be affected by cloud clusters. The atmospheric processes investigated were on three scales; the C-scale for features of the order of 1 km to 10 km, the B-scale for features of the order of 10 km to 100 km and the A-scale for those of 100 km to 1000 km. The ships, which were allocated by the various countries to the Experiment, were divided according to their individual capabilities for monitoring the physical processes on one or more of these scales. Ships ranged from oceanographic research vessels with radar and, perhaps, the capability of flying a tethered balloon and deploying buoys (and so possessing the sophistication of equipment necessary to examine the fine C-scale structure of the atmosphere), to ships with the relatively simpler instrumentation suitable for measurement on the A-scale. The latter were distributed round the inner core of C-scale ships at 08° 30′N, 23° 30′W, and across the Atlantic, to monitor the passage of synoptic-scale features through the GATE area.

The United Kingdom A-scale ships

The two sister ships chartered by the Meteorological Office as part of the UK contribution were based at Lowestoft. Their tonnage of 477 tons made them amongst the smallest ships taking part. The *Charterer* and *Endurer* of Gardline Shipping Ltd sailed from Lowestoft in early June fully equipped to undertake the main requirements of A-scale ships. Scientific stores for the whole three-month period were carried. These included 180 cylinders of helium with which the balloons used for the upper-air ascents were filled, the balloons themselves, and the many ancillary stores required. In addition, the holds of the ships had been modified to hold extra fresh-water tanks and a deep-freeze capacity which was to make them virtually self-sufficient in most food items for the entire period. The working space for the equipment and staff was in the stern one-third of the ship and measured some 6 metres by 2½ metres. Six scientific staff were carried and one technician. In addition, since one of the requirements was for data to be disseminated in real time, two radio operators were provided to transmit all meteorological data to the communications ships. These latter, with their more powerful transmitters, collected and retransmitted the data from several ships to the GATE Operations Centre at Dakar. (See Plates III and IV.)

Instrumentation and observations

Both UK ships were required to make a surface observation every hour throughout the time they were in the GATE area. Each ship was provided for this purpose with instruments which had been well tried on ocean weather ships. A standard cup and vane Mk IV anemometer was mounted on the cross-tree of the mainmast, with readings displayed on dials in the office. Pressure was measured with precision aneroid barometers. Perhaps uniquely among the ships taking part, we also had a static pressure head mounted on the cross-tree and connected to the precision aneroids; this reduced to a large extent pressure fluctuations which might otherwise have occurred in aneroids mounted in the closed interior of a ship. Sea temperatures were sampled with a canvas bucket and thermometer. In addition, we used an infra-red thermometer. This instrument, which was hand-held, gave the temperature of an object at which it was pointed as a reading on a dial. Calibration before use was a simple operation involving the exposure of the instrument to a 'black-body' maintained at a constant temperature. Strictly this instrument gave the 'sea-skin' temperature. These readings, in conjunction with knowledge of the global incoming short-wave and long-wave radiation, may allow a reasonable estimate of radiation balance to be made.

Air temperature was measured by using mercury-in-glass thermometers in standard marine screens exposed on both bridge wings. Readings from these were supplemented by additional ones from electrical resistance thermometers (ERTs). The ERT readings were recorded once a minute on the chart of a 'Kent' recorder.

A rain-gauge was also carried. The collecting funnel was mounted on the cross-tree and any rain collected was passed down a plastic tube to the bridge where it activated a peristaltic pump; each action of the pump was registered as an 'event' on magnetic tape which also bore one-minute time marks. A crude magnetic-tape record of both rate and duration of rainfall was thus

obtained. A cumulative total of rainfall events was also registered by an electromagnetic counter. Rainfall was measured every six hours while the ships were occupying their nominal positions. Expendable bathythermographs were used to measure sea temperatures to a depth of 400 metres. The results of these soundings were recorded on a strip chart. One sounding a day was made during Phases I and II but this was increased to eight a day during Phase III. Additionally, while the ships were *en route* to and from assigned positions, soundings were made at intervals of approximately 60 nautical miles. The results of one of the soundings made in a day were transmitted to Dakar.

Upper-air soundings were normally made four times a day at 00, 06, 12 and 18 GMT. A reduced program of two soundings a day was made during passage to and from our positions. These were all reported to Dakar as soon as the ascent had been computed and encoded. The soundings gave temperature, pressure and humidity with wind data, to an average height of 20 kilometres. The equipment used for these soundings was new and its greatest asset was that winds could be measured without the necessity of installing on the ships a stabilized radar—a prohibitively expensive operation. Winds were determined by using standard navigational radio methods (Navaid) to measure the small displacements of the radiosonde transmitter. In our case, and for the GATE area generally, the equipment was designed to use either VLF navigational signals or Omega signals. The accuracy of the system depended on its being able to receive reliably the signals from three stations appropriately located. This was not always possible. Because hand computation of winds took an unduly long time, the equipment contained a small computer. Ships of other nations also used this equipment and so there was a measure of uniformity which is not always possible to achieve in an international operation.

Global incoming short-wave and long-wave radiation was also recorded. A good exposure of the instruments used for these measurements was difficult to obtain. They were eventually mounted on top of the wheel-house although it was still possible for masts and aerials to cast shadows over the sensitive elements. However, with the ceaseless rolling of the ship, the average effect of these was small. The pyranometers were mounted in damped gimbals to reduce the effect of rolling and pitching. The outputs from the radiation instruments were continuously recorded on a potentiometric recorder.

A final experiment, in which both UK ships were involved, was on behalf of the University of Miami. This was an aerosol sampling program designed to determine how much and in what circumstances Saharan dust is carried across the North Atlantic to the Caribbean area where it has been detected. Again, a suitable exposure for the sampling equipment was difficult to find on such small ships but a reasonable compromise was effected in the end. The experiment was a simple one with a filter being changed once a day and photometer readings being taken from time to time.

Results and problems

The success of an individual A-scale ship contribution to GATE is difficult to assess until an analysis of its results against the whole field of observations is possible. This must take time, but the data are being processed to a tight schedule defined in the GATE plan. With such an ambitious program it was inevitable that some failures occurred. There are few ships which can claim

complete adherence to their schedule. The planned program was itself altered during the course of the Experiment to take account of unforeseen situations in the weather or to respond to some difficulty or failure among the ships. The UK ships had their share of troubles too. Recalcitrant generators giving unstable outputs (or on one occasion none at all), failing air conditioning, which entailed equipment (and people) working in temperatures for which they were not designed, and vibration, which we had anticipated to a certain extent, but which, in the end, took its slow, inevitable toll of the electromechanical parts of our instruments. Much was learnt in these respects which will be of value in the future. On the positive side, both UK ships made over two hundred upper-air ascents to an average height of over 20 kilometres. Some of these data were difficult to assess at the actual time, owing to uncertainties arising in the output from the computer. The post-Experiment analysis now being carried out will probably reveal more usable detailed data than was originally thought possible. One of the benefits of the system we used for upper-air ascents was that almost all the original data were stored on magnetic tape. It will be possible to re-examine these raw data and clarify those points of difficulty which occurred during the actual Experiment.

Surface observations at the required frequency were maintained throughout the time the ships were in the GATE area. Rainfall measurement, difficult enough at a land station, is likely to yield the least reliable of our data. The appreciable cooling in the surface sea temperature that was noted during heavy rain will raise interesting questions. Some 250 successful bathythermograph soundings were made by each ship. Radiation, both long-wave and short-wave, was successfully recorded during the Experiment. It had been hoped to log these data automatically on paper tape but this did not prove possible. The aerosol sampling program was completed to the satisfaction of the University of Miami. The scale of dust transport from the Sahara is difficult to visualize. During some of the more vigorous outbreaks the effects are very noticeable, with convection much suppressed, a marked diminution of incoming radiation and the sun reduced to a milky ball. On one occasion at 15°N 35°W the ship itself was covered in a fine red dust. It is hoped that with the increased number of data resulting from the GATE observations this phenomenon will be better understood.

Despite the difficulties, a reasonable degree of success was achieved. The A-scale ships, by the very nature of their responsibilities, worked independently. The data they collected and broadcast were used by the GATE Operations Centre to prepare the synoptic analyses used in the planning of the daily experiments involving aircraft, and those experiments requiring an enhanced observation program on the ships. They were also used by the special group at Bracknell for their 11-layer mathemetical model of the tropical atmosphere in as near to real time as communications allowed. These were the immediate and successful uses to which the data were put. But it is also in the longer term that the quality and usefulness of our data will be judged. The weather ranged from steady north-east trades in the north of the GATE area, to generally cloudy, disturbed conditions with torrential rain near the ITCZ further south. Within this general pattern were fluctuations that only careful scrutiny of the data will reveal.

Conclusion

Much has been said and written about meteorology being one of the few examples of genuine international co-operation. Never was this more fully demonstrated than by the example of GATE where experiences and difficulties, shared on a personal basis, must have made even more secure the foundations laid in previous years. The friendliness and help that we on the UK ships enjoyed during our in-port periods at Dakar provided a personal and immediate stimulus to the spirit of co-operation upon which the Experiment had been so successfully based.

International emblem of GATE

The design shown above, which has been printed on the covers of this and the previous issue of the *Meteorological Magazine*, is the international emblem of GATE and was used extensively in and around the main operations base at Dakar, Senegal. Beneath the compass points—indicated by their initial letters in French which is the official local language—there is a diagrammatic representation of a baobab tree, the national emblem of Senegal. 'E.T.G.A.' is the French version of 'GATE' and is formed from the initial letters of 'Expérience Tropicale GARP Atlantique'. The wreath or chaplet of leaves is the United Nations symbol as used in the official emblem of WMO.

The following announcement has been received from the GARP Activities Office of the World Meteorological Organization:

ANNOUNCEMENT OF THE GATE VISITING SCIENTIST PROGRAMME ADOPTED BY THE TROPICAL EXPERIMENT BOARD

(VIIIth Session, Geneva, 4–6 May 1976)

The success of an international experiment like GATE requires not only the exchange of data, but also an exchange of ideas, theories, and the practical details of instrument design and calibration. After the initial analyses of national data, nations can greatly benefit by arranging the exchange of scientists involved in GATE. Therefore, the Tropical Experiment Board (TEB) at its VIIIth session (Geneva, 4–6 May 1976) endorsed and adopted the 'GATE Visiting Scientist Programme'.

The Programme is an opportunity for scientists who are working on GATE-related problems (e.g. theory, numerical modelling or data analysis) to continue their work at an institution in another country. Although the Programme is orientated towards one of the five Sub-programme Data Centres, the opportunities are not limited to those institutions.

Scientists who are interested in this opportunity may contact their national GATE 'focal points' and the institution which they desire to visit. They should also write to the GARP Activities Office (GAO) and include a *curriculum vitae* or professional résumé, a summary of the proposed work or research project, the name of the desired institution and a proposal for the length of visit. The role of the GAO will be to bring the credentials of the individual to the attention of the institution quickly and to coordinate subsequent arrangements.

At the present time there are opportunities at the following institutions:

Canada:	Department of Physics, University of Toronto, Toronto.
France:	The Oceanographic Sub-programme Data Centre, Brest.
F.R.G.:	The Max-Planck Institute for Meteorology and the Meteorological Institute of Hamburg University, Hamburg.
U.K.:	Meteorological Office, Bracknell.
U.S.A.	Many Universities, Research Centres and U.S. Government Research Laboratories.
U.S.S.R.:	Hydrometeorological Research Centre, Moscow. Main Geophysical Observatory, Leningrad. State Oceanographic Institute, Moscow.

Financial support for these visits and exchanges (including travel and *per diem* payments) must be worked out on an individual basis. The selection of the individual will depend on the needs and interests of the host institution; the decision rests with the host alone.

LETTER TO THE EDITOR

An improved wind-direction indicator

Readers have pointed out that some of the statements in our recent paper (Moulsley, Fryer and Pike, 1976*) need some clarification, especially the sentence immediately following equation (10) on page 149. The Royal Aeronautical Society report cited gives graphs of normal force coefficient C_N (Figure 8) versus angle of incidence α for various values of b/c. Our equation (9) is an approximate algebraic representation of the slopes of the graphs as a function of b/c. Our choice of 20 for a value of b/c was arbitrary and not entirely justified from the limited range of values for the graphs but it is probably about the limit from practical considerations. Even with this optimistic value for b/c the conclusion is that the support rod needs to be quite long for critical damping to be achieved. We should have written '$dC_N/d\alpha$ = rate of change of normal force coefficient with angle' rather than '$dc/d\alpha$ = rate of change of lift coefficient with angle'. We apologize for this ambiguity but we believe the general argument to be valid as evidenced by the behaviour of the device in practice.

National Institute of Agricultural Engineering,
Wrest Park,
Silsoe,
Bedford MK45 4HS.

L. J. MOULSLEY

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* MOULSLEY, L. J., FRYER, J. T. and PIKE, K. S.; An improved wind-direction indicator. *Met Mag*, **105**, 1976, pp. 148–153.

REVIEW

Our changing climate, by John Gribbin. 150 mm × 210 mm, pp. 95, *illus.*, Faber and Faber, 3 Queen Square, London WC1N 3AU, 1975. Price: £2.75.

For very good reasons climatic change has become in recent years a very topical subject. But the pressing need to understand past changes and predict future ones does not automatically mean that instant solutions are now at hand. It is particularly regrettable to find a book which is aimed at young people giving this impression and conveying a very unbalanced account of this complex issue.

This book will certainly leave the reader with the impression that all changes of climate are due to changes in solar activity. Since the incoming solar radiation is the prime energy source for the earth's atmosphere this *seems* an eminently sensible conclusion. The author, however, does not spare a page in which to discuss the relation between the total energy coming from the sun and the sunspot number. While this relationship remains undetermined there is no secure physical basis for a relation between climate and sunspot number. The relation has to be established statistically with all the attendant dangers

of sampling and chance relations arising from averaging. In most cases significance tests show that the relationship between the climatic series, whether temperature, rainfall, pressure, or circulation strength, and the sunspot number could have arisen by chance. There are moreover unexplained changes in phase which should be a warning against making predictions based on a constant phase relationship. This low statistical significance means that even if the relationship is a real one it explains only a small part of the variability. It is therefore quite misleading to attribute the changes in climate entirely or mainly to variations in the number of sunspots as the author of this book has done.

There is no mention of the likelihood even of changes arising from internal effects, that is to say within the earth–sea–atmosphere system. Yet the heat stored in the oceans is so large that there could well be variations in the rate of transfer to the atmosphere capable of producing many of the climatic fluctuations. And there is not a word about the effect on climate of variations in global cloud cover, atmospheric carbon dioxide and water vapour, or the possible effect of changing turbidity due to dust—volcanic, natural and man-made. Yet careful studies have shown that all these effects must be at least considered in the attempt to explain past climatic changes.

The climatic forecast with which the book concludes emphasizes and crowns with a conical cap the author's lack of judgement in this book. Such a forecast is based entirely on the secular cycle in sunspot activity. The relation of climate to this is not securely established. If it is real it does not explain all the variability and it is foolish and unscientific to ignore all the other factors which could affect the outcome.

M. K. MILES

HONOUR

The following award to a recently retired member of the Meteorological Office was announced in the Queen's Birthday Honours List, 1976:

M.B.E.

Mr I. A. Nixon, who at the time of his retirement was a Higher Scientific Officer at Kirkwall Airport, Orkney.

AWARD

Award of IMO Prize to Academician Ye. K. Fedorov

We note with pleasure that the twenty-first International Meteorological Organization Prize for outstanding work in meteorology and in international collaboration has been awarded this year to Academician Yevgeny Konstantinovich Fedorov, formerly Head of the Hydrometeorological Service of the USSR and at present Director of the Institute of Applied Geophysics of the Academy of Sciences of the USSR.

OBITUARIES

It is with regret that we have to record the death on 30 May 1976 of Dr P. A. Einstein, Senior Scientific Officer, and the death on 23 June 1976 of Mr W. P. Moss, Photographer, both of Met O 16.

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked 'For Meteorological Magazine'.

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PRECIPITATION CLIMATOLOGY OF THE TEHRAN AREA

By A. KHALILI
(University of Tehran, Faculty of Agriculture, Karaj, Iran)

SUMMARY

The rainfall climatology of the Tehran area, based on precipitation data for the period from 1894 to 1974, was studied. The probabilities of occurrences of selected amounts of annual and monthly precipitation were estimated and presented, using the Gaussian and gamma distributions respectively. The secular trend of annual precipitation was checked. A series of monthly, seasonal and annual isopleth maps concerning precipitation and the distribution of the numbers of rainy days were analysed for the five-year period beginning in 1969. No notable tendency was found for more frequent occurrences of rainy days or for maximum precipitation over the city. On the contrary, the existence of a peculiar phenomenon of the 'jump-over' of rainy areas over the city seems to be confirmed. Evidence of decreases induced by urbanization was found in the number of weakly rainy days for the city centre of Tehran and is discussed.

1. INTRODUCTION

This work has been undertaken with the following two goals in mind:

(a) A statistical investigation of the monthly and annual precipitation data for Tehran.

(b) A mesoclimatological study of daily, monthly, seasonal and annual precipitation within a radius of 30 to 60 km of the city's centre, in order to establish whether any unusual values potentially related to urban effects appeared to be present.

For the first part only monthly and annual precipitation data for Tehran from 1894 to 1974 were used. Observations for Mehrabad Airport made by the Iranian Meteorological Organization date back only to 1944. Before this date the data were obtained from the British Embassy and from *World Weather Records*. The missing months, with interrupted records, which were very few, were reconstructed by using mean monthly values.

According to Hashemi (1969) the rainfall measurements of Mehrabad Airport and the British Embassy are considered as homogeneous for the purpose of climatological study, and all calculations based on these records are performed without regard to the precise station to which the data refer.

For mesoclimatological study of the Tehran area daily precipitations of selected urban and suburban meteorological stations during the period 1969–73 were used. It seems here that the homogeneity of data for all stations will overcome the shortness of the periods. The locations of these stations are shown in Figure 1.

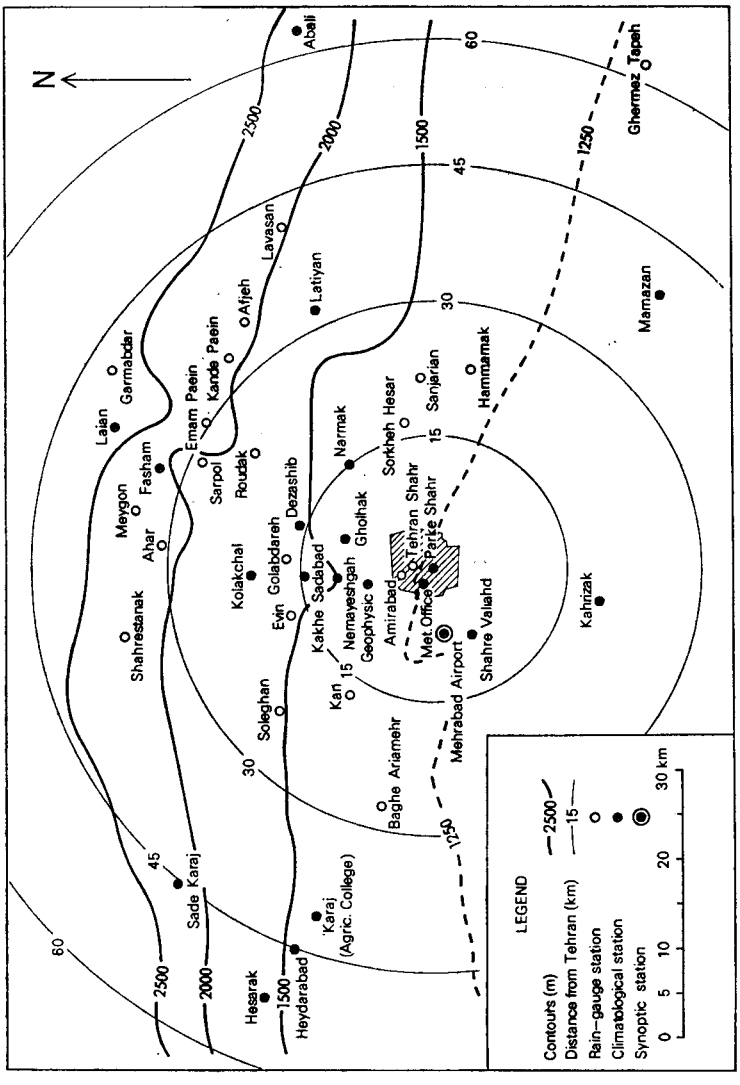

FIGURE 1—LOCATION OF STATIONS USED IN THIS STUDY

A review of research works reveals that, as yet, no study has been performed concerning the effect of Tehran city on precipitation. The lack of densely spaced precipitation stations with good historical records and the difficulties associated with delineating orographic effects (which are very important in this area) are the primary reasons for so little research on urban effects. But for some other regions of the world the subject has been studied by various authors: Changnon, 1968; Woollum, 1968; Sekiguti and Tamiya, 1969; Huff and Changnon, 1973, etc.

2. Precipitation climatology of Tehran

Monthly precipitation analysis

Table I shows the mean monthly precipitation of Tehran for the period 1894–1974. The annual regime of rainfall is a semi-mediterranean type which is characterized by a dry period (June–October) and a principal maximum in January or March. Forty-nine per cent of the precipitation occurs during the winter-time (January, February and March).

TABLE I—MONTHLY MEAN VALUES OF PRECIPITATION IN MILLIMETRES FOR TEHRAN (1894–1974)

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
39·6	34·7	40·5	31·9	15·2	2·8	2·9	1·6	1·4	7·7	24·2	31·7

In order to obtain further information about the monthly precipitation of Tehran the gamma distribution was used. The probability of receiving a monthly value of precipitation equal to or greater than a selected value of X millimetres in this model is

$$P(x \geqslant X) = \frac{m}{(m+n)\beta^{\alpha+1}\Gamma(\alpha+1)} \int_0^X x^{\alpha} e^{-x/\beta}\, dx, \quad \ldots \quad (1)$$

where

n is the number of wet months
m is the number of dry months
$\Gamma(\alpha + 1) = \alpha!$ is the ordinary gamma function.

The parameters α and β may be estimated as follows.
Let the rainfall of the ith wet month be x_i.
Define the arithmetic mean of all the x_i by

$$M(x) \equiv (x_1 + x_2 + \ldots + x_n)/n, \quad \ldots \quad (2a)$$

their geometric mean by

$$G(x) \equiv (x_1 x_2 \ldots x_n)^{1/n}, \quad \ldots \quad (2b)$$

and a quantity A by

$$A \equiv \ln \{M(x)/G(x)\}. \ldots \quad (2c)$$

Then

$$\alpha = A^{-1}\{0{\cdot}25 + 0{\cdot}144(3 + 4A)^{\frac{1}{2}}\} - 1 \quad \ldots \quad (3)$$

$$\beta = M(x)/(1 + \alpha). \ldots \quad (4)$$

Values of α and β derived in this way are good approximations to their maximum likelihood estimates (Thom, 1958).

The observed and calculated frequencies were subjected to the chi-square test for January, April, July and November only. No significant differences were found. These results were accordingly generalized, and the model was used for all 12 months. The values of X corresponding to the various selected constant probability levels were calculated for each month by using Pearson's tables (1946), and the results are presented in Table II, which gives detailed information about the monthly precipitation of Tehran.

TABLE II—CALCULATED AMOUNTS OF MONTHLY PRECIPITATION WHICH HAVE A GIVEN PROBABILITY OF BEING EXCEEDED

Probability	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						millimetres						
0·05	100·4	94·5	91·8	84·9	86·6	10·0	4·5	9·8	8·1	28·6	70·0	103·1
0·10	79·9	75·0	73·0	66·5	36·5	7·5	2·5	5·7	5·2	20·0	59·8	80·4
0·20	57·5	56·0	55·0	49·5	27·0	4·2	0·0	2·5	1·0	13·2	36·2	59·5
0·40	36·7	32·5	35·5	35·5	16·5	0·0	0·0	0·0	0·0	4·5	21·9	35·4
0·50	30·0	24·5	27·0	27·0	12·5	0·0	0·0	0·0	0·0	1·5	15·5	27·5
0·60	22·5	18·0	23·5	21·5	9·1	0·0	0·0	0·0	0·0	0·0	11·7	21·3
0·80	11·5	9·0	12·5	12·5	3·0	0·0	0·0	0·0	0·0	0·0	3·1	10·4
0·90	6·0	4·5	7·5	6·5	1·5	0·0	0·0	0·0	0·0	0·0	0·0	5·5
0·95	3·5	1·7	5·5	2·5	1·0	0·0	0·0	0·0	0·0	0·0	0·0	3·1

Annual precipitation analysis

The annual precipitation of Tehran varies between 91 and 560 mm but the probabilities of obtaining these extreme values are very low.

The following are some statistical parameters of the annual precipitation of Tehran.

Mean: $x = 234{\cdot}2$ mm.
Standard deviation: $S_x = 88{\cdot}7$ mm.
Coefficient of variation CV: $= 100\, S_x/^x = 37{\cdot}9$.

The frequency distribution of annual precipitation during the period under study has been examined. The unimodal aspects of the frequency histogram (which is not shown here) suggest that it could be successfully fitted to the Gaussian distribution. The calculated and theoretical frequencies were subjected to the chi-square test. The computed chi-square with four degrees of freedom was 8·13 and the tabulated chi-square with the same number of degrees of freedom at the 5 per cent level was 9·49. It was therefore concluded that the differences between theoretical and observed frequencies were not significant.

The probabilities (in per cent) of receiving amounts of annual rainfall equal to or less than (or equal to or more than) X mm of rain were calculated respectively from the following equations:

$$P(x \leqslant X) = 0{\cdot}4499 \int_{-\infty}^{X} \exp\{-6{\cdot}35 \times 10^{-5}(x - 234{\cdot}2)^2\}\, dx \quad . . \qquad (5)$$

$$P(x \geqslant X) = 0{\cdot}4499 \int_{X}^{+\infty} \exp\{-6{\cdot}35 \times 10^{-5}(x - 234{\cdot}2)^2\}\, dx \ldots \quad (6)$$

The results of these calculations are presented in Figure 2.

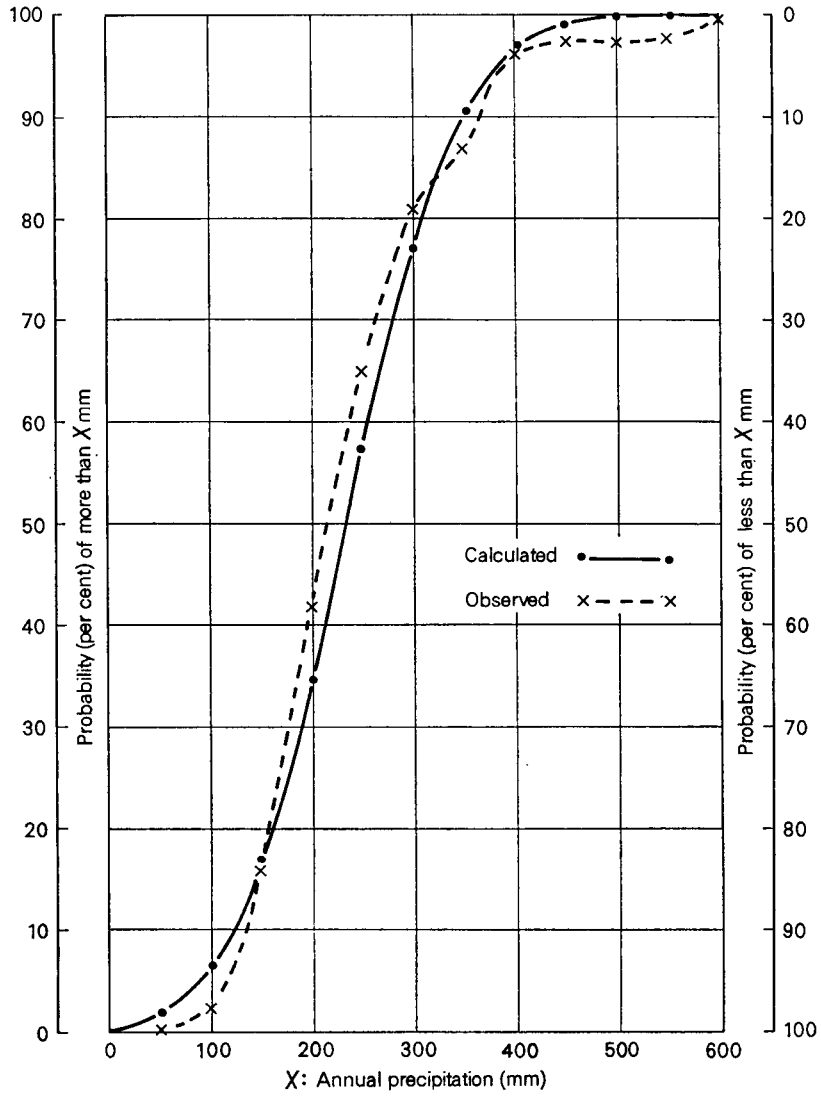

FIGURE 2—CUMULATIVE PROBABILITIES OF ANNUAL PRECIPITATION OF TEHRAN (1894–1974)

To gain further insight into year-to-year variation of annual rainfall the time-series of data were plotted as in Figure 3. To reduce the amount of variation present in the set of annual precipitation data and estimate the trend the moving averages of order 15 years were calculated and attributed to the mid year of each of the 15-year periods and plotted in Figure 3. This figure shows an increase of annual rainfall during the period 1916–28, and a relative decrease from 1920 to 1960, followed by a slight increase up to 1974, with, however, some moderate oscillations.

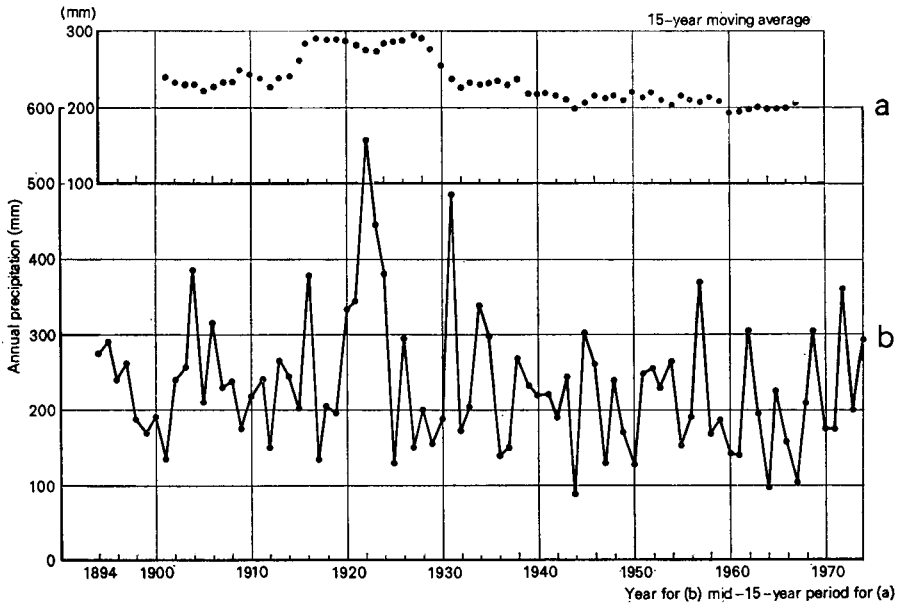

FIGURE 3—ANNUAL PRECIPITATION AND SECULAR TREND

3. Precipitation climatology of the Tehran area

The basic precipitation parameters employed in this part are the mean annual, seasonal and monthly values of (a) the usual expression for average rainfall in millimetres, (b) the number of rainy days with daily precipitation equal to or more than 0·1 mm and (c) the number of rainy days with daily precipitation equal to or more than 1 mm.

To calculate these parameters the daily values of precipitation for urban and suburban stations marked in Figure 1 for the five years starting in 1969 were checked statistically. Data for some stations were omitted because of important shortcomings in the records, and the short, interrupted records of some other stations were constructed by using the linear regression method. The records of 14 stations were completed and they served as principal points for study.

Finally the annual, seasonal and monthly distribution maps of the above-mentioned three parameters were drawn and compared. The analysis was therefore based on a total of 42 maps.

Major findings

In the northern part of the Tehran area the amount of precipitation increases with altitude and the orographic effects could be clearly seen during almost all periods. The values of increasing gradient have been reported by Khalili (1972). But in many cases no notable tendency was found for higher values of precipitation over the city in comparison with the rural areas to the east, south and west which have approximately the same elevation. Contrary to expectation, the existence of (a) a cell of minimum precipitation over the city which extends between Parke Shahr and Kan, and (b) a lower amount of precipitation over the city, seems to be confirmed. However, the probability of both of the above-mentioned phenomena is 53 per cent. Figure 4 shows the annual average rainfall pattern of the Tehran area.

The frequency distribution maps of the average number of rainy days (daily precipitation $\geqslant$ 0·1 mm*) demonstrate a minimum number of rainy days over or north-east of the city during almost all periods of the year. For example, data from the period under study on the frequency of rainy days showed that the rural stations averaged 17 more measurably rainy days than the urban stations' average of 43 days. The difference is significant at the 5 per cent level. Figures 5 and 6 illustrate two typical examples of the mean annual and seasonal frequency patterns of the number of rainy days.

A similar study was undertaken of the number of moderately rainy days (daily precipitation $\geqslant$ 1 mm*). The moderately rainy day frequencies seem to be higher during the cold period and lower during the rest of the year; some isopleth maps, however, showed a reverse result. The average number of moderately rainy days was 35 a year downtown and 40 a year in the surrounding stations (Figure 7), but the difference is not so significant as for the days with the lower rainfall.

A comparison of mean monthly precipitation parameters, carried out between Parke Shahr situated downtown and Mehrabad Airport station, which is located 7 km west of the city centre and at an equal elevation, confirmed the previous results (Figure 8a–c) especially the lower mean values of the number of rainy days in Parke Shahr during almost all months which seem to be an effect of urbanization.

Generally, the spatial and temporal variation of precipitation amounts shows a greater similarity to the variation in the number of moderately rainy days than to the variation in the number of rainy days.

Furthermore, a comparison was made of the monthly values of precipitation amount, number of rainy days and number of moderately rainy days for both the above-mentioned stations. The absolute and relative frequencies of months with positive, negative and zero differences are presented in Table III. This table reveals a highly significant predominance of the negative difference frequencies for the monthly number of rainy days and supports, once more, the hypothesis of decreases produced by urbanization in the number of light rains. The negative frequencies are also moderately higher for both the other parameters, but not to a significant extent. Similar results were also reported for Japanese cities by Sekiguti (1970).

* These are called 'rain-days' and 'wet days' by the United Kingdom Meteorological Office (Editor).

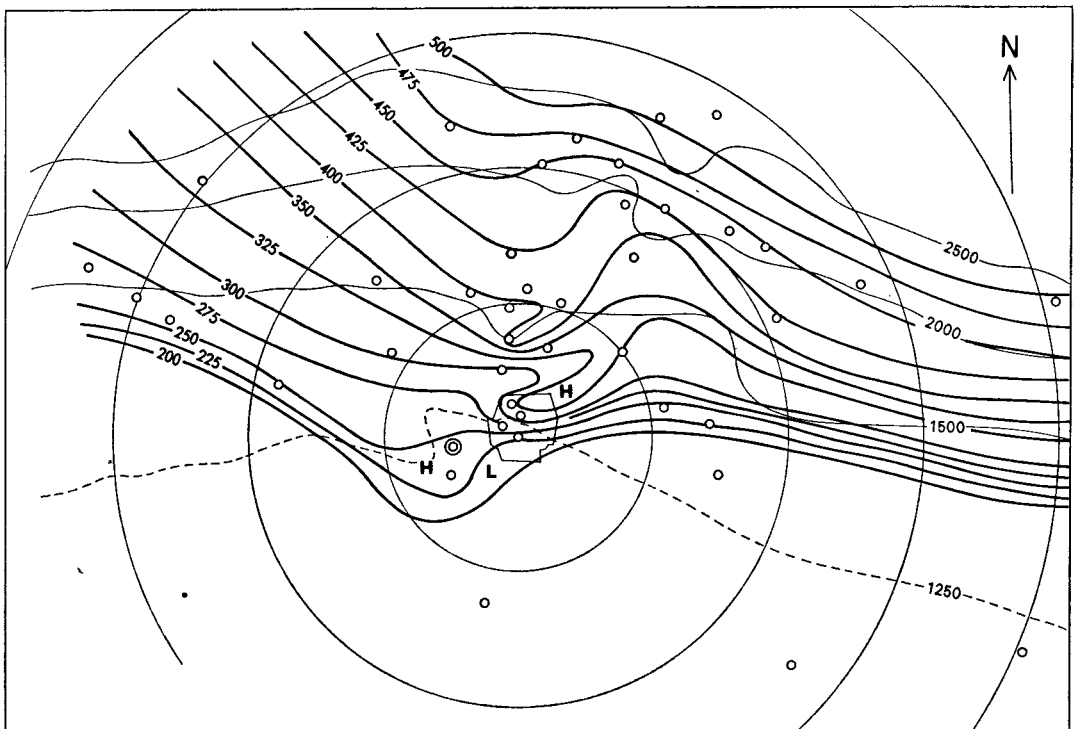

FIGURE 4—ANNUAL PRECIPITATION PATTERN IN MILLIMETRES OF THE TEHRAN AREA (1969–73)

The isopleth corresponding to 375 mm was omitted from the original diagram; the author has confirmed that the printed isopleths are correctly numbered.

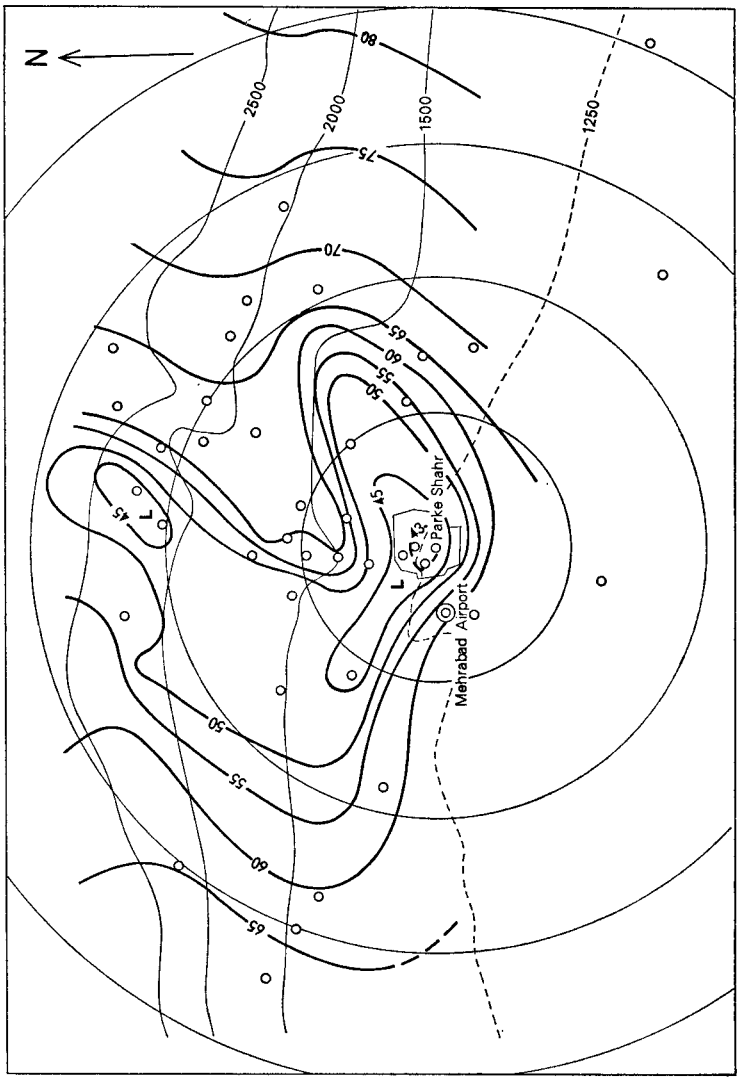

FIGURE 5—AVERAGE ANNUAL NUMBER OF RAINY DAYS ($\geqslant$0·1 mm) IN THE TEHRAN AREA (1969–73)

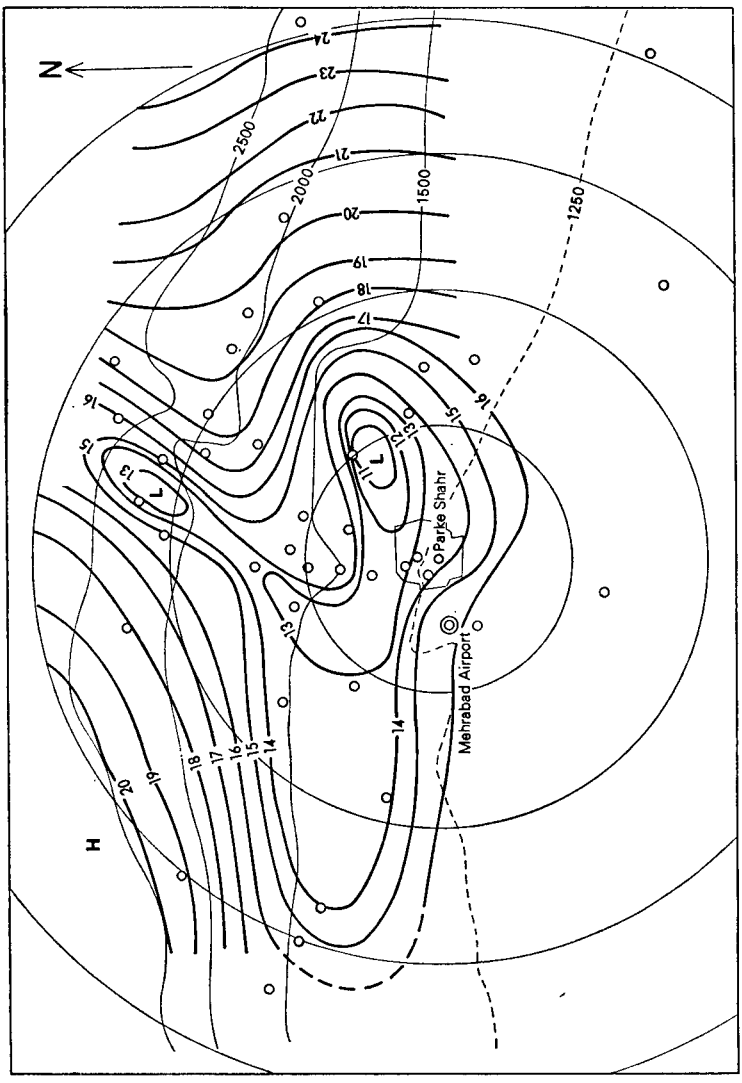

FIGURE 6—AVERAGE SEASONAL NUMBER OF RAINY DAYS (OCTOBER, NOVEMBER AND DECEMBER) IN THE TEHRAN AREA (1969–73)

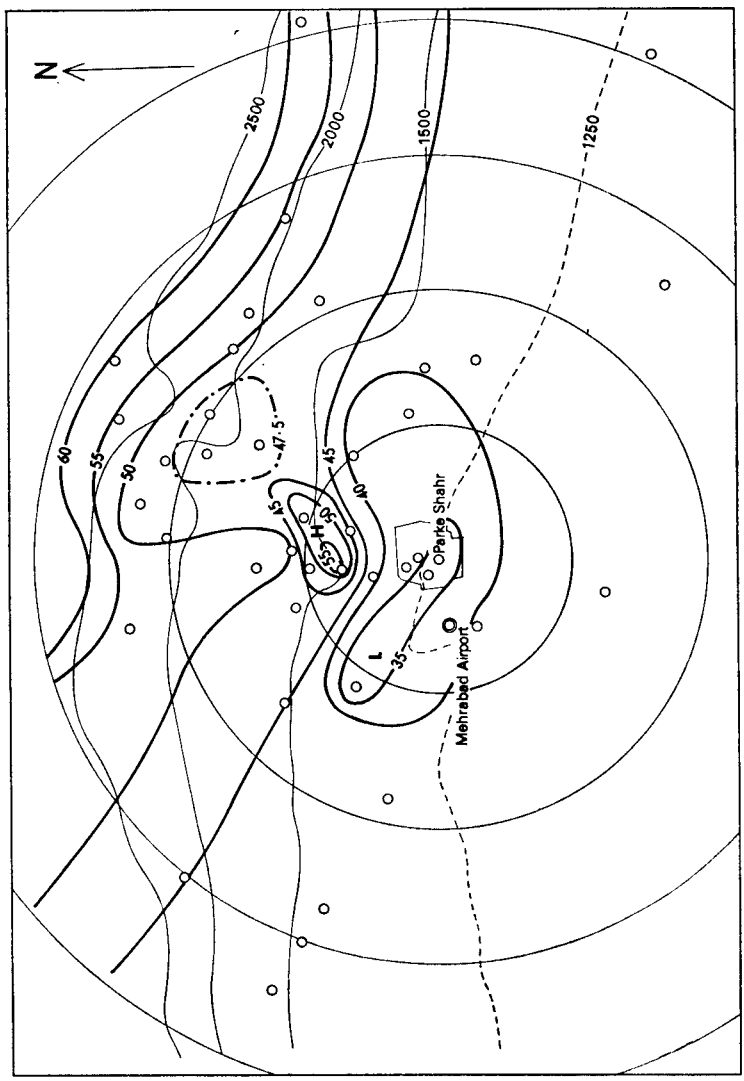

FIGURE 7—AVERAGE ANNUAL NUMBER OF MODERATELY RAINY DAYS WITH DAILY PRECIPITATION EQUAL TO OR MORE THAN 1 mm (1969–73)

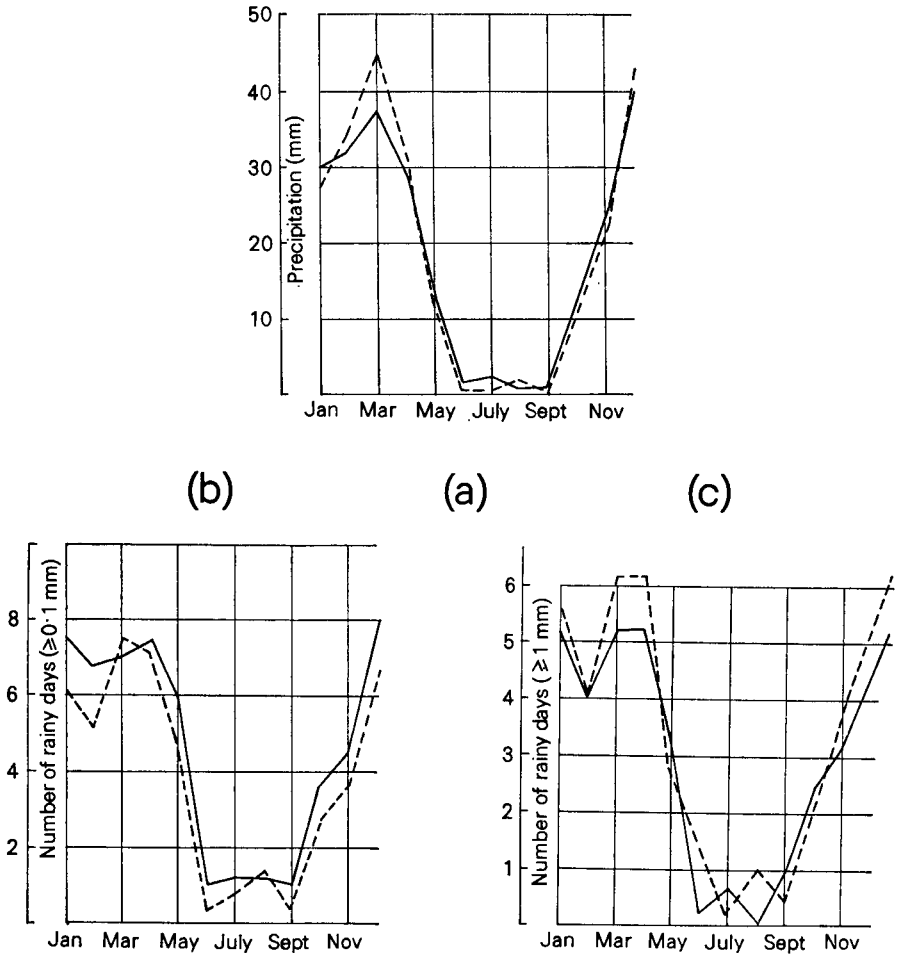

FIGURE 8—MONTHLY MEAN VARIATION OF PRECIPITATION AMOUNT, NUMBER OF RAINY DAYS AND NUMBER OF MODERATELY RAINY DAYS IN DOWNTOWN AND RURAL TEHRAN

(a) Precipitation amount

(b) Number of rainy days (≥0·1 mm)

(c) Number of moderately rainy days (≥1 mm)

—— Parke Shahr (downtown)

– – – Mehrabad Airport (rural)

4. Conclusions and discussions

This study provided evidence of the less frequent occurrence of the number of rainy days with daily precipitation equal to or more than 0·1 mm in the downtown section of Tehran during almost all months. The mean decrease in

TABLE III—COMPARATIVE FREQUENCY DISTRIBUTIONS (NUMBER OF MONTHS) OF THE PRECIPITATION PARAMETERS AT PARKE SHAHR (CITY) AND MEHRABAD AIRPORT (SUBURB) IN THE PERIOD FROM 1969 TO 1973

	City < Suburb	City > Suburb	City = Suburb
	−	+	o
Amount of precipitation	28 (47%)	22 (37%)	10 (16%)
Number of rainy days ≥ 0·1 mm	30 (50%)	13 (22%)	17 (28%)
Number of moderately rainy days ≥ 1 mm	17 (28%)	16 (27%)	27 (45%)

the number of rainy days was about 17 days a year (19 per cent) which was found to be statistically significant. The above-mentioned decrease occurred mostly during the cold period of the year. This result is not in agreement with those found in American and European studies, which have shown an increase of rainy days over cities.

As far as the annual mean values are concerned, the study provided little evidence of urban decrease effects on precipitation amounts as well as on the number of moderately rainy days over the city. On the contrary, some low monthly increases were observed for both the above-mentioned parameters, and these increases occurred mostly during the cold period of the year. It seems here that the annual and monthly values of precipitation are not related to the number of rainy days but rather closely related to the number of moderately rainy days. The spatial and temporal distributions of precipitation parameters confirmed the above-mentioned discovery. In conclusion, important decreases observed in the number of rainy days, over the downtown area, are not due to daily moderate and excessive rainfall but especially due to the number of days with light rain (between 0·1 and 1 mm rainfall a day).

By compiling the above-mentioned findings, we could offer the following hypothesis for explaining the plausible town-produced decreases in the number of light rains:

'The climate of Tehran is dry, and the relative humidity is generally low there. That is why the probable concentration of condensation and freezing nuclei over urban areas is not capable of producing some detectable changes in precipitation amounts.'

On the other hand, the urban thermal effects and the existence of the heat island over the city during the whole year have been pointed out as a primary result of a research project undertaken by the Iranian Meteorological Organization. Although the atmospheric instability due to this heat island is not able to produce the intense ascending air movement and consequently to intensify cloud formation because of air dryness, it is capable of evaporating the smaller raindrops suspended in the atmosphere and thus reducing the number of rainy days over the urban area of Tehran. The installation of a densely spaced meteorological station network is required to define more precisely the various urban effects on precipitation in Tehran.

ACKNOWLEDGEMENT

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THE FIRST COLD SNAP OF AUTUMN

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(European Space Operations Centre, Darmstadt, Federal Republic of Germany)

SUMMARY

The first cold snap (as defined) in autumn has a mean date for most places near sea level in England and Wales in the first 10 days of November. The distribution about the mean date is in many places bimodal with one mode around the end of October and the second some 10 to 15 days later. At most places, 90 per cent of occasions lie within ±15 days of the mean. At stations with a long record the mean date for the 50 years 1921 to 1970 is some 2 to 3 days later than the mean date for the 50 years 1871–1920. Early dates are brought about by a northerly plunge over the United Kingdom, but later dates arise from a cold easterly airstream. On any occasion the first cold snap advances in a series of surges and averaged over many years, the mean date with increasing altitude is progressively earlier and amounts to one day for every 17½ metres of increased altitude.

Maps of the mean, earliest and latest dates (reduced to sea level by applying the correction) are shown. From them, the mean dates can be deduced for any place.

INTRODUCTION

In examining the structure of a forecast for the autumn season, it was considered that it would be useful to forecast the first cold snap of autumn since this could affect the milk yield of dairy herds. Also such a cold snap would be of interest to fuel and power suppliers since it would be related to a rapid increase in demand.

Definition

The date of the first cold snap at a place is defined as the second day of two consecutive days on both of which the day maximum screen temperature fails to exceed 9°C (48°F). This definition approximates to the type of weather occurring when dairy cattle, left out in the fields, have been known to suffer a loss of milk yield (L. P. Smith, private communication).

FREQUENCY DISTRIBUTION OF THE FIRST COLD SNAP BY PENTADS

The daily observed maximum screen temperatures for the places given in Figure 1, from the commencement of record (*c.* A.D. 1870) were examined and

FIGURE 1—LOCATION OF STATIONS USED IN THE INVESTIGATION

the annual dates of the first cold snap, determined according to the definition, were classified in groups of 5 days (pentads). Table I gives the distribution for a number of places in England. The range covered is about 11 to 14 pentads, i.e. a period of about two months, from the second week in October to the second week in December. At some of the stations in the table the distribution is bimodal with one maximum at the end of October (pentads 60 or 61) and a second maximum about 15 days later. An examination of all the stations used showed that for 70 per cent of them (28 out of 40) the distribution was bimodal. All but Plymouth, Penzance, Scilly and Haverfordwest had the first maximum in pentad 60 or 61. At all places except Southampton the second maximum was 10 to 15 days after the first. The places which did not show a bimodal distribution were all in the eastern half of England.

Secular change

Figure 2 gives the 10-year (running) means of the date of the first cold snap for Oxford from 1862, and Durham from 1881. The two graphs are similar with minima around 1896, 1927 and 1955, and maxima around 1907, 1945 and 1965, with a range of about 15 days. The fluctuations appear to have a periodicity of just under 30 years but an apparent periodicity of between 20 and 30 years is to be expected when 10-year moving averages are used (see Brooks and Carruthers, 1953). It is not proposed to make a statistical investigation into the reality or otherwise of this periodicity but merely to point out that fluctuations do occur. The fluctuations are caused by changes in the atmospheric circulation and Figures 3 to 5 give the circulation departures for a 10-year period when the mean date was early and for one when it was late. Figure 3 gives the mean pressure departure for October for the 10 years 1887 to 1896 from the mean for the period 1873–1968. The anomalous northerly gradient brought cold air from the north and hence increased the chance of two days with maxima $\leqslant 9°C$. Figures 4 and 5 give the mean pressure departure for October and November respectively for the 10 years 1956 to 1965. By contrast, October for these 10 years shows a negative anomaly south-east of Greenland and a positive anomaly over central Europe. The anomalous south-west flow over and to the north of Scotland indicates a decreased frequency of northerly winds. November for the 10 years shows anomalous high pressure from north Norway to Greenland. Continental air from the east brought late cold snaps.

Table II gives the mean date for a number of places with long records for the period from commencement of record to 1920 and for the period 1921–70. The average date for the second period is 2 to 3 days later than for the first.

At Oxford all the 10-year means before 1901 are earlier than 5 November. After 1901 only the periods ending in 1926–28 and 1950–59 have means earlier than 5 November. The mean for the period 1853 to 1900 is 2 November and for the period 1901–70 the mean date is 8 November.

These figures are consistent with the general warming of the climate in central England noted by the author (1972) for the months October to March. The fall of mean temperature from October to November for central England is about 3·5 K, i.e. about 0·12 K per day. The rise in mean October temperature from the period 1871–1920 to the period 1921–70 is about 0·75 K and for November about 0·25 K, giving an average change of about 0·35 K for the end of the first week of November and hence a delay of some 3 days in the average onset of the first cold snap.

TABLE I—FREQUENCY DISTRIBUTION OF FIRST COLD SNAP OF AUTUMN BY PENTADS

	No. of years	Pentad number	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	Average date
			Sept.		October						November						December				
		from	23	28	3	8	13	18	23	28	2	7	12	17	22	27	2	7	12	17	
		to	27	2	7	12	17	22	27	1	6	11	16	21	26	1	6	11	16	21	
Oxford	102		—	—	—	1	2	6	11	17	16	14	18	9	4	2	—	1	—	1	6 Nov.
Cambridge	98		—	—	—	1	1	5	13	15	16	15	14	11	6	—	1	—	—	—	6 Nov.
Southampton	116		—	—	—	—	—	3	4	15	12	18	18	23	9	7	1	5	—	1	13 Nov.
Ross-on-Wye	91		—	—	—	1	—	6	15	14	14	15	13	10	1	1	1	—	—	—	5 Nov.
Southport	79		—	1	—	2	1	3	14	8	12	14	12	7	3	—	—	2	—	—	6 Nov.
York	93		—	—	—	2	1	11	14	14	16	17	12	4	1	—	—	1	—	—	3 Nov.
Durham	99		1	—	2	3	6	14	20	16	16	11	5	5	—	—	—	—	—	—	29 Oct.

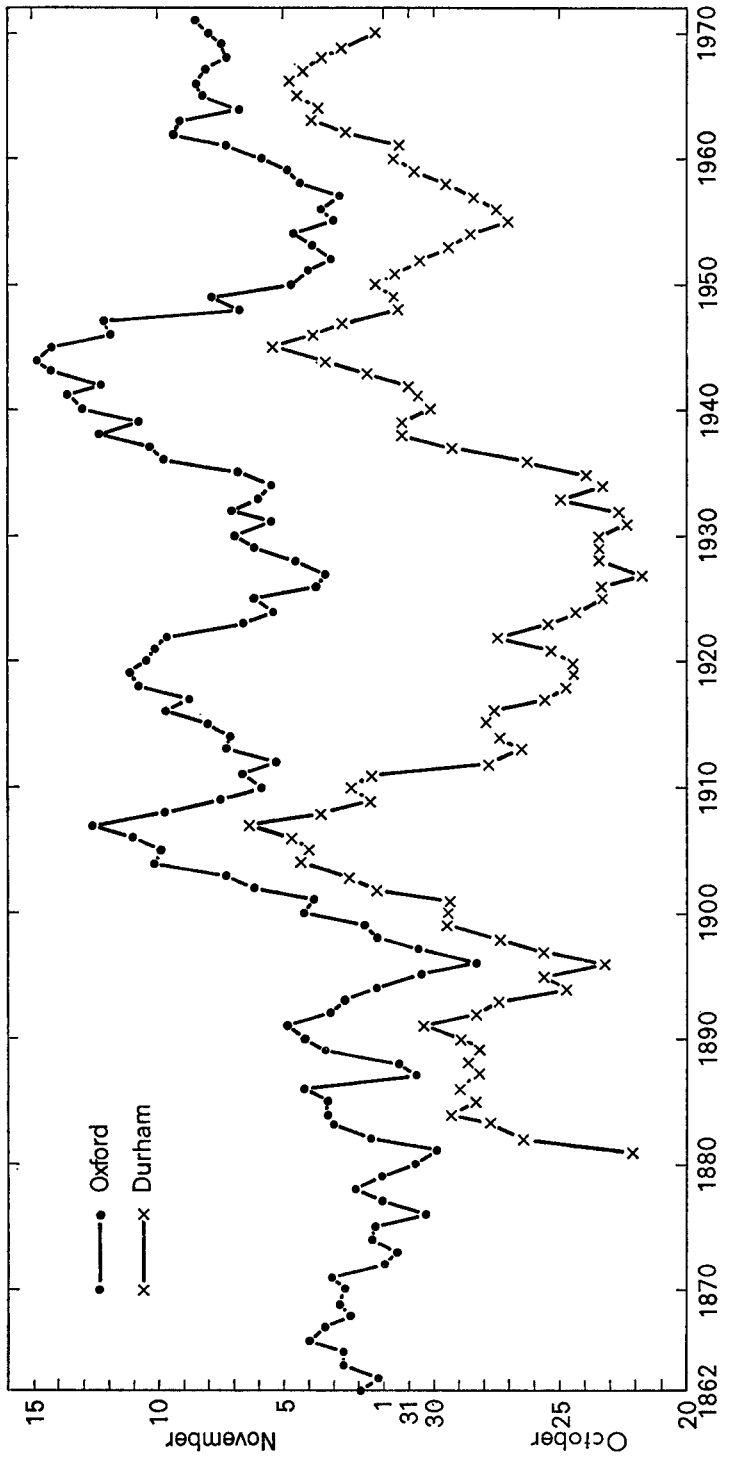

FIGURE 2—10-YEAR RUNNING MEANS OF THE DATE OF THE FIRST COLD SNAP AT OXFORD AND DURHAM
Plots refer to the 10-year period ending in the year named.

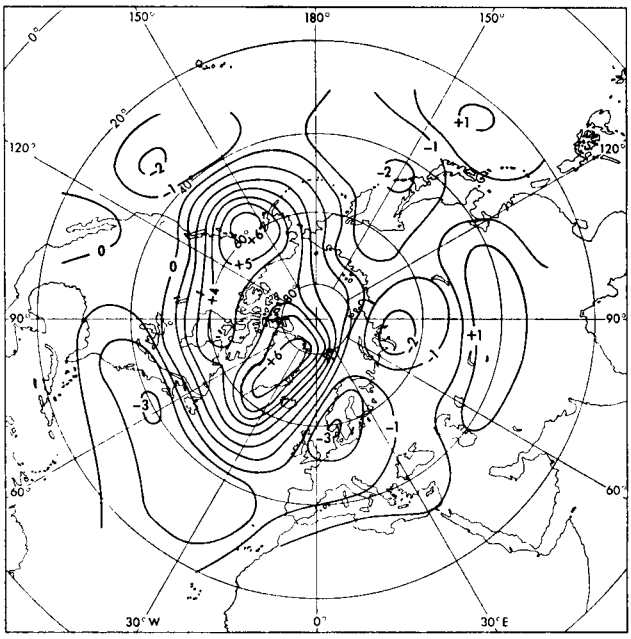

FIGURE 3—MEAN-SEA-LEVEL PRESSURE ANOMALY FOR OCTOBER 1887–96
Departures in millibars are measured with respect to the mean October values for the period 1873–1968.

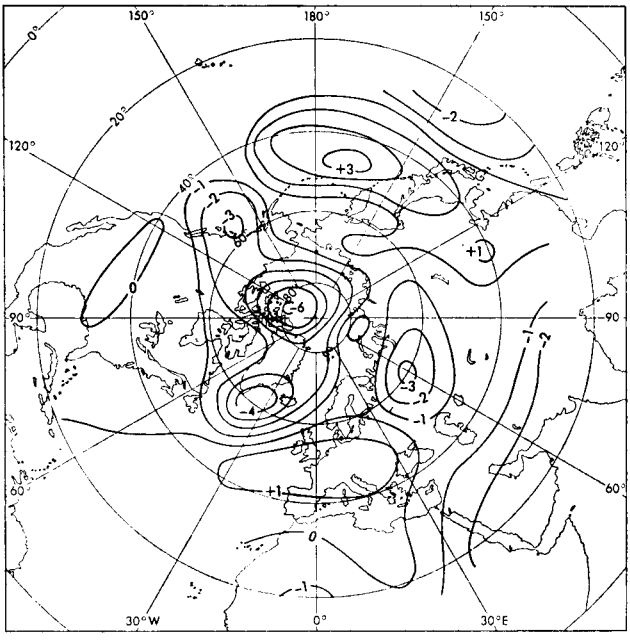

FIGURE 4—MEAN-SEA-LEVEL PRESSURE ANOMALY FOR OCTOBER 1956–65
Departures in millbars are measured with respect to the mean October values for the period 1873–1968.

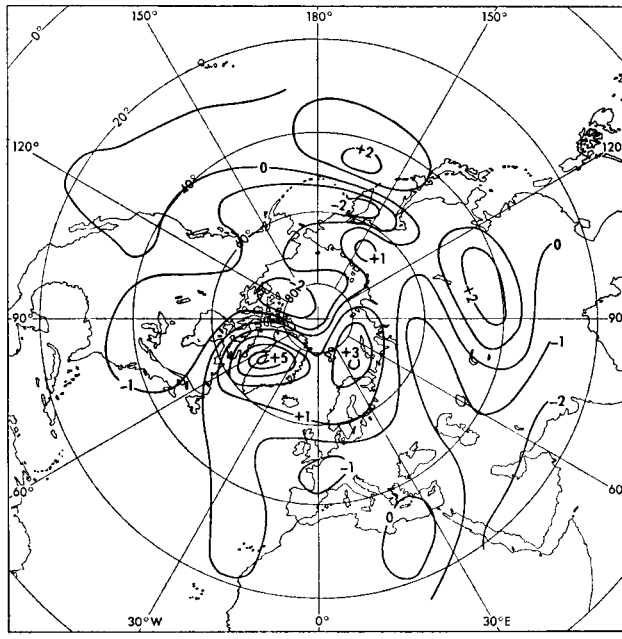

FIGURE 5—MEAN-SEA-LEVEL PRESSURE ANOMALY FOR NOVEMBER 1956–65
Departures in millibars are measured with respect to the mean November values for the period 1873–1968.

TABLE II—MEAN DATE OF THE FIRST COLD SNAP FOR THE PERIODS 'UP TO 1920' AND '1921 TO 1970'

Place	Mean date up to 1920	Number of years	Mean date 1921–70	Difference *days*
Durham	28 October	49	30 October	+2
York	2 November	43	4 November	+2
Douglas	5 November	43	5 November	0
Bidston	30 October	47	3 November	+4
Buxton	18 October	45	21 October	+3
Spurn Head	3 November	42	5 November	+2
Gorleston	4 November	48	9 November	+5
Oxford	5 November	50	8 November	+3
Cambridge	7 November	48	5 November	−2
Kew	4 November	40	7 November	+3
Cheltenham	3 November	43	4 November	+1
Ross-on-Wye	5 November	41	5 November	0
Hastings	9 November	47	13 November	+4
Southampton	12 November	50	15 November	+3
Plymouth	19 November	48	24 November	+5

WEATHER SITUATIONS ASSOCIATED WITH EARLY AND LATE DATES

Figure 6 gives the mean-sea-level pressure map averaged over the following days in October:

1908	20th	1931	18th	1948	22nd
1917	22nd	1933	22nd	1949	27th
1926	16th	1939	21st	1951	18th

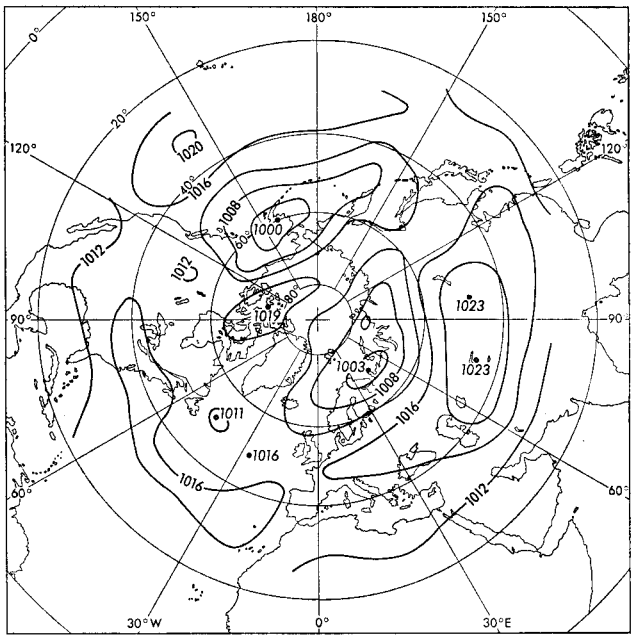

FIGURE 6—MEAN-SEA-LEVEL PRESSURE MAP FOR 'EARLY DAY −5'

Isopleths are averaged over 20 Oct. 1908, 22 Oct. 1917, 16 Oct. 1926, 18 Oct. 1931, 22 Oct. 1933, 21 Oct. 1939, 22 Oct. 1948, 27 Oct. 1949 and 18 Oct. 1951.

These dates are 5 days before the date of the first cold snap (in those particular years) at Kew, Cambridge and Nottingham. This mean chart (for day −5) shows low pressure in the southern Barents Sea, a westerly flow across the United Kingdom, a weak ridge in the Atlantic, low pressure east of Newfoundland and high pressure in the Canadian Arctic. Figure 7 shows the mean for one day later (day −4). The Newfoundland low has moved to 25°W with a trough to the Azores, the ridge is crossing the UK and high pressure has spread into northern Greenland. Figure 8 shows the mean for (day −3). The low has continued into southern Scandinavia and high pressure has spread further over Iceland with northerly winds as far as Scotland. The trough over the Azores has formed a cut-off centre. Figure 9 (day −2) shows the Azores low spreading eastwards whilst the first break of northerlies has moved into Denmark and northern Germany. Figure 10 (day −1) shows a fall of pressure over France and a north to north-east airstream over England. On this day, the maximum temperatures failed to reach 9°C. Figure 11 (day 0) shows an intensification of the system over Europe so that maximum temperatures fail to reach 9°C for the second day running.

Figure 12 gives the mean-sea-level pressure map averaged over the following days in November:

1896	17th	1914	17th	1936	14th
1899	13th	1916	11th	1954	16th
1902	12th	1932	16th	1963	16th
1907	15th				

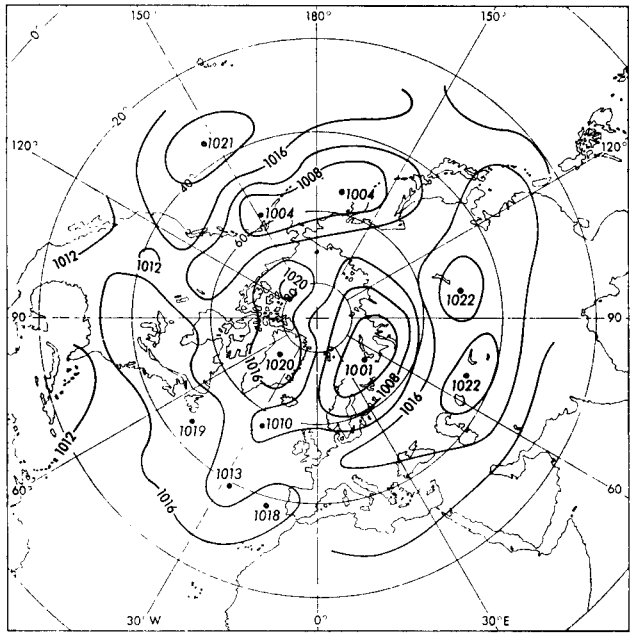

FIGURE 7—MEAN-SEA-LEVEL PRESSURE MAP FOR 'EARLY DAY —4'

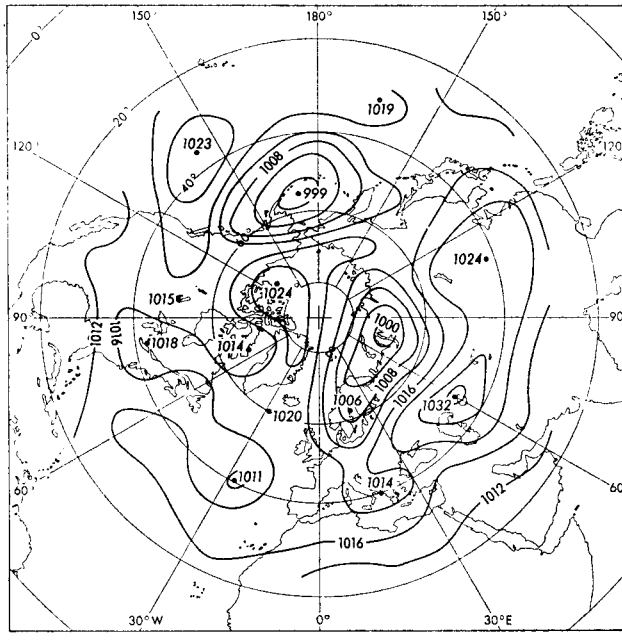

FIGURE 8—MEAN-SEA-LEVEL PRESSURE MAP FOR 'EARLY DAY —3'

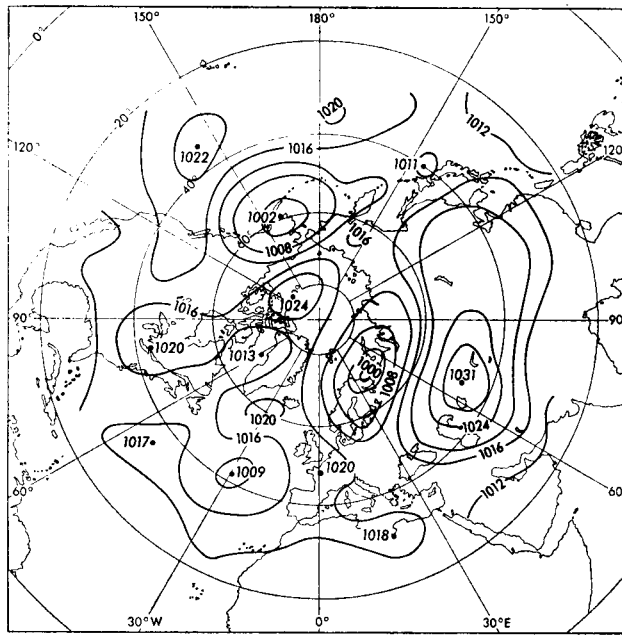

FIGURE 9—MEAN-SEA-LEVEL PRESSURE MAP FOR 'EARLY DAY —2'

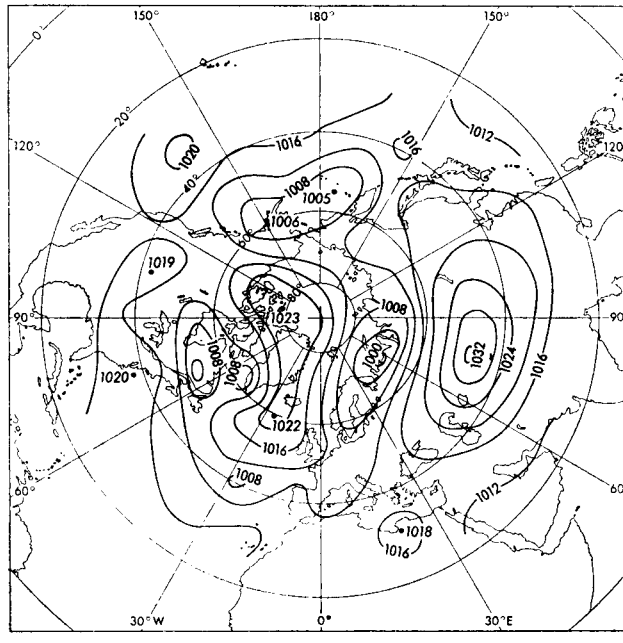

FIGURE 10—MEAN-SEA-LEVEL PRESSURE MAP FOR 'EARLY DAY —1'

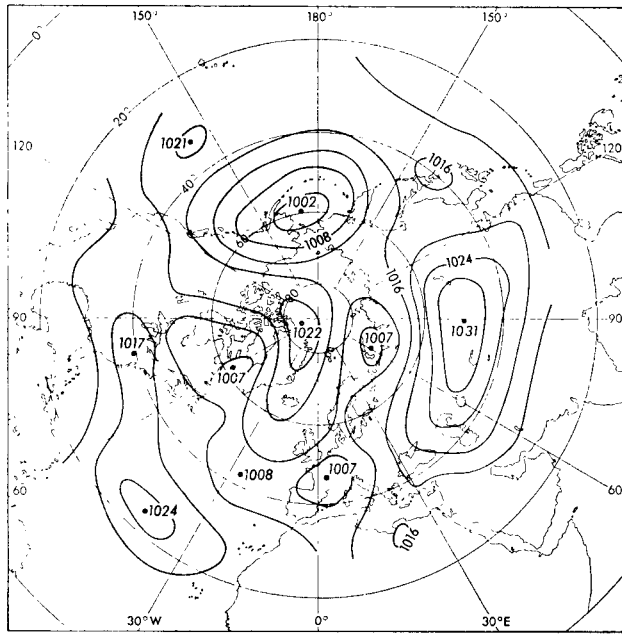

FIGURE 11—MEAN-SEA-LEVEL PRESSURE MAP FOR 'EARLY DAY 0'

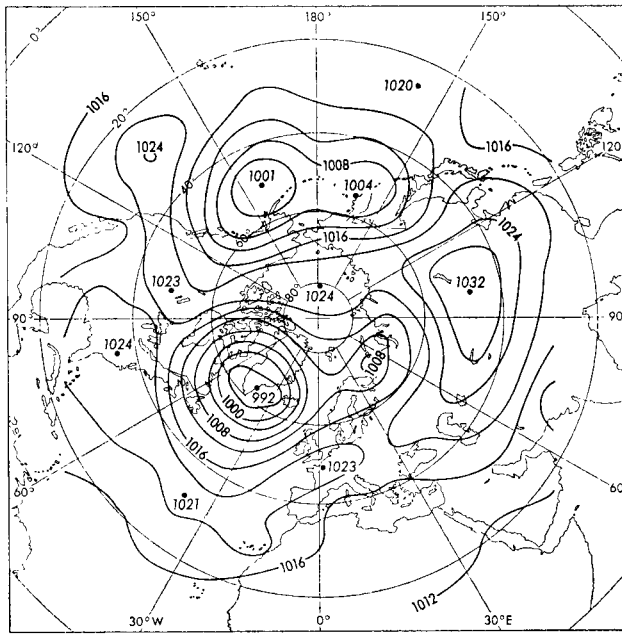

FIGURE 12—MEAN-SEA-LEVEL PRESSURE MAP FOR 'LATE DAY −5'
Isopleths are averaged over 17 Nov. 1896, 13 Nov. 1899, 12 Nov. 1902, 15 Nov. 1907, 17 Nov. 1914, 11 Nov. 1916, 16 Nov. 1932, 14 Nov. 1936, 16 Nov. 1954 and 16 Nov. 1963.

These dates are 5 days before the date of the first cold snap (in those particular years) at Kew, Cambridge and Nottingham. On (day −5), in great contrast to Figure 4, pressure is low over southern Greenland and high over France and Spain, giving a south-westerly flow over the UK. On (day −4) and (day −3) (Figures 13, 14) pressure rises slowly over Scandinavia. On (day −2) (Figure 15) the main centre of high pressure is over north-west Russia. On (day −1) (Figure 16), pressure is high over the Baltic and a cold easterly airstream has reached England. On this day the maximum temperatures failed to reach 9°C. Day 0 (Figure 17) shows an intensification of the easterly flow so that the maximum temperatures again failed to reach 9°C.

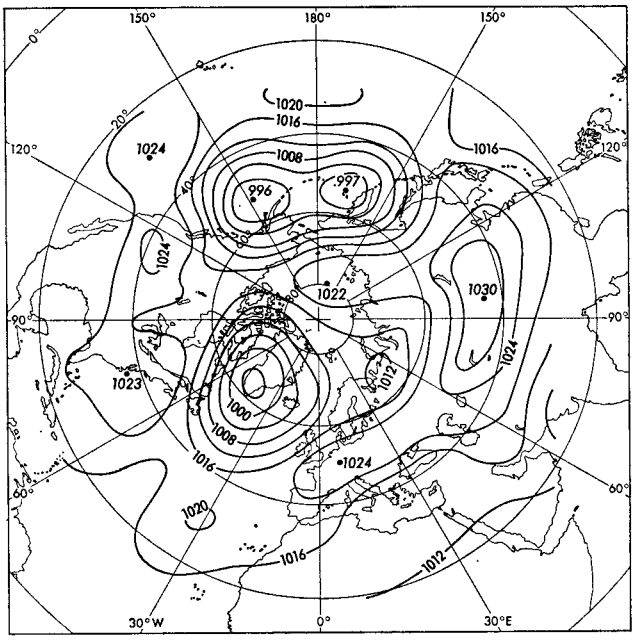

FIGURE 13—MEAN-SEA-LEVEL PRESSURE MAP FOR 'LATE DAY −4'

The bimodal nature of the distributions at a large number of stations probably arises because the annual decline of temperature is such that with high pressure over Iceland and northerlies over the UK, maximum temperatures in those northerlies will fail to reach 9°C over the UK by about the third or fourth week of October. On the other hand, with low pressure over Greenland/Iceland, the maximum temperatures in the easterly/south-easterly airstreams that may occur over England continue to reach 9°C until about the second week of November.

Variation of first cold snap with altitude

On any occasion, the first cold snap advances southwards over the UK in a series of surges. For example, in 1970 the first surge occurred on 21 October, bringing the first cold snap to most of northern England and the Midlands. The second surge occurred between 12 and 15 November, bringing the first cold

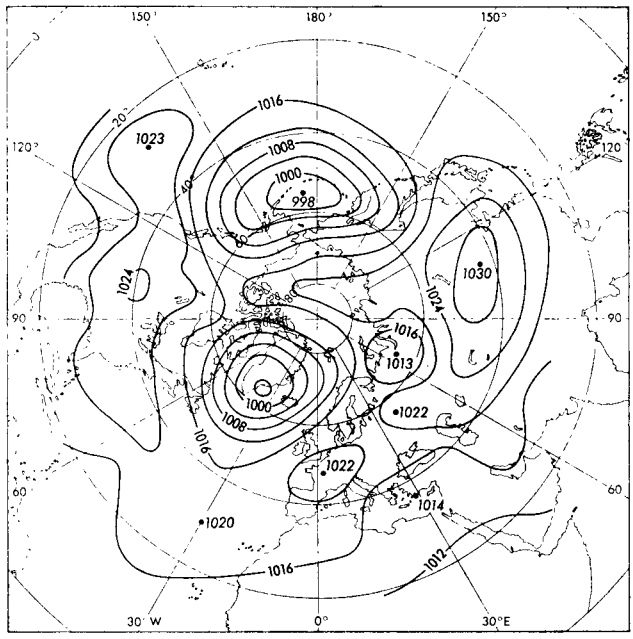

FIGURE 14—MEAN-SEA-LEVEL PRESSURE MAP FOR 'LATE DAY —3'

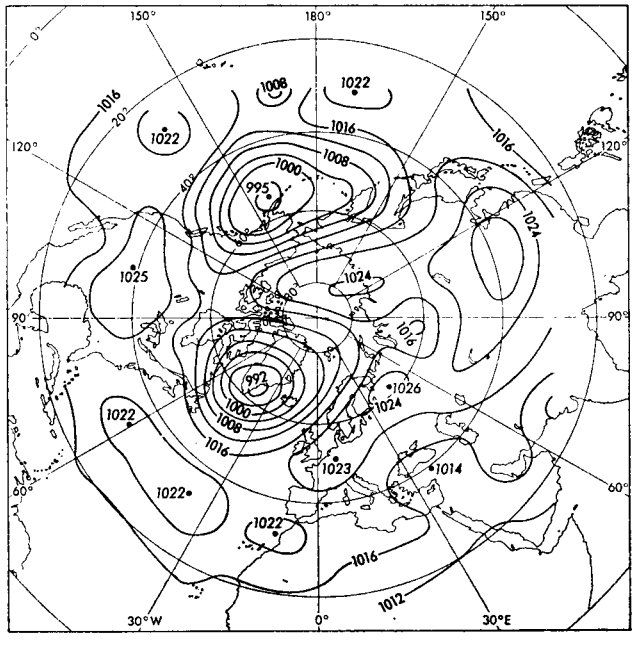

FIGURE 15—MEAN-SEA-LEVEL PRESSURE MAP FOR 'LATE DAY —2'

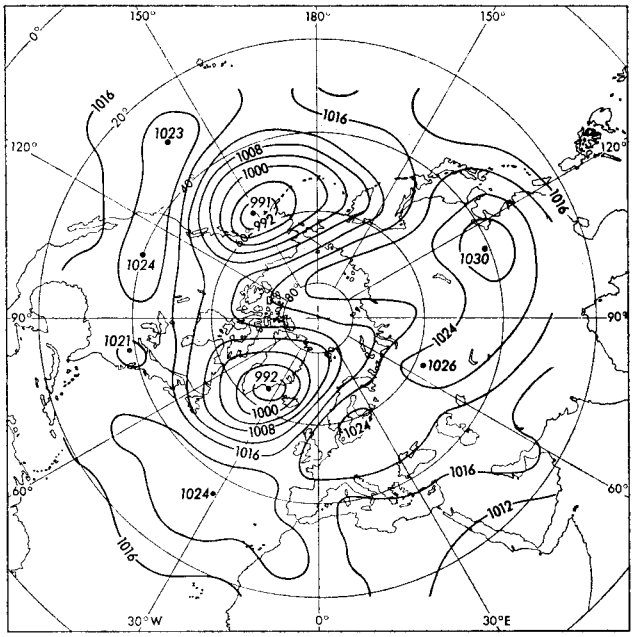

FIGURE 16—MEAN-SEA-LEVEL PRESSURE MAP FOR 'LATE DAY —1'

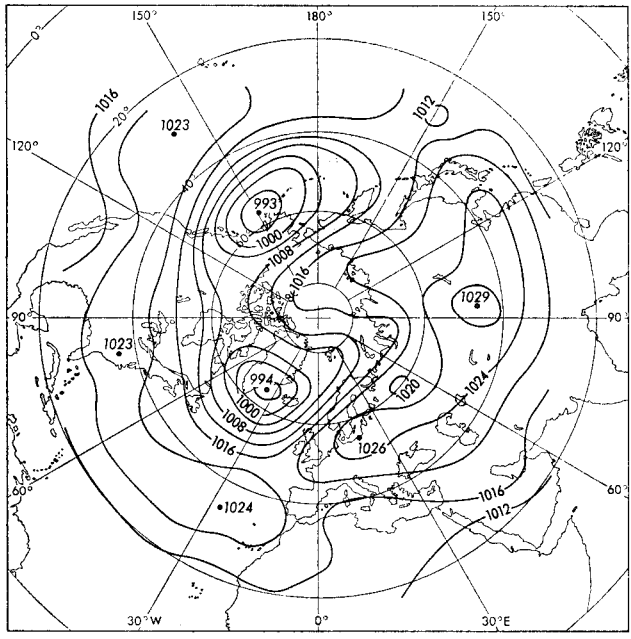

FIGURE 17—MEAN-SEA-LEVEL PRESSURE MAP FOR 'LATE DAY 0'

snap to the remainder of north-west England, all eastern England and further parts of southern England and South Wales. The third surge occurred on 9 December, bringing the first cold snap to the remainder of southern England and South Wales except for extreme south-west Cornwall.

The higher the altitude of a station the greater the chance of it being affected by the first surge. In the example just given Shaftesbury, at an altitude of 220 m, experienced its first cold snap in the first surge whereas Bath and Reading, at 26 m and 47 m respectively, did not. Averaged over a number of years, the mean date will occur earlier at a higher-level station than at a lower-level station nearby.

By comparing nearby stations at different altitudes, it is possible to form an estimate of how much earlier the first cold snap occurs as altitude increases. Table III gives the difference in days between the mean date of the first cold snap at neighbouring stations at different altitudes:

TABLE III—DIFFERENCE IN DAYS BETWEEN THE MEAN DATES OF THE FIRST COLD SNAP OF NEIGHBOURING PAIRS OF STATIONS AT DIFFERENT ALTITUDES

Stations	Height difference *metres*	Days difference	Average per day *metres*
Bradford and York	116	6·96	16·7
Buxton and Nottingham	248	14·48	17·1
Birmingham and (Oxford + Nottingham)	120	6·61	18·1
Rothamsted and Kew	108	6·34	17·0
Shaftesbury and (Bath + Southampton)	187	9·77	19·1

This table gives an average of 17·5 metres per day*. This value compared with that deduced by using a change of 3·5 K from October to November in the mean temperature for central England and a standard-atmosphere lapse rate of 6·5 K/km, which gives a value of 17·65 metres per day.

Using this correction of one day for every 17·5 metres of altitude, Figure 18 gives isopleths of the mean date (reduced to sea level), based on some 40 stations in England and Wales over the period 1921–70. North of the Thames Valley, the mean (sea level) date is between 5 and 10 November, but north-east England (Northumberland, Durham and Yorkshire) have a mean date before 5 November. Only the south coast, south-west England and the south-west corner of Wales have a date after 15 November.

Figures 19 and 20 give isopleths of the third earliest and third latest dates (reduced to sea level) in the 50-year period 1921–70. About 90 per cent of years fall within these dates, and for most places they are about 15 days before and after the mean date, except in south-west England where the range increases to near 30 days.

* Text printed as received. Table III in fact yields a value of 17·6 m/day and using this value might have slightly modified Figure 18 (Editor).

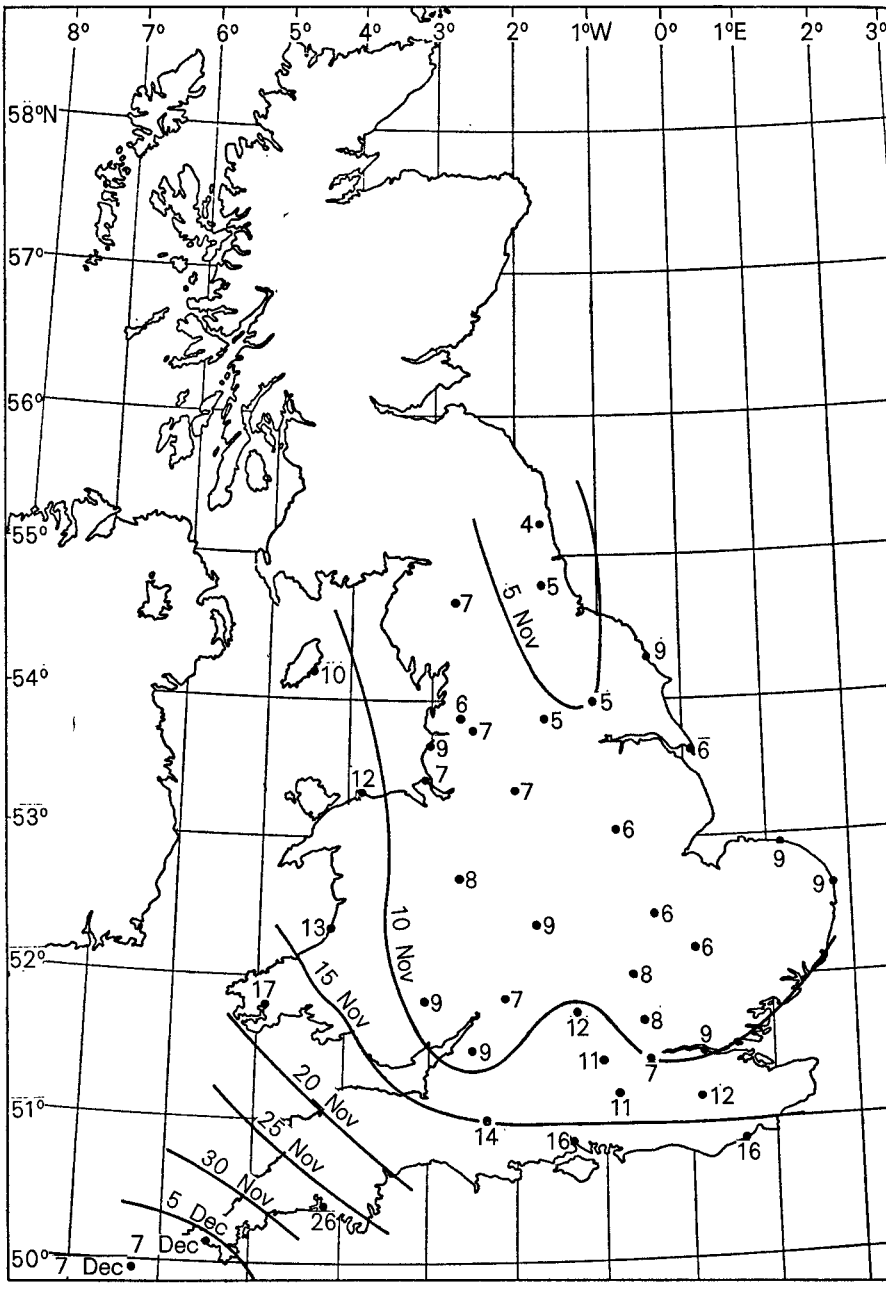

FIGURE 18—MEAN DATE OF FIRST COLD SNAP OF AUTUMN (REDUCED TO SEA LEVEL) IN THE PERIOD 1921–70

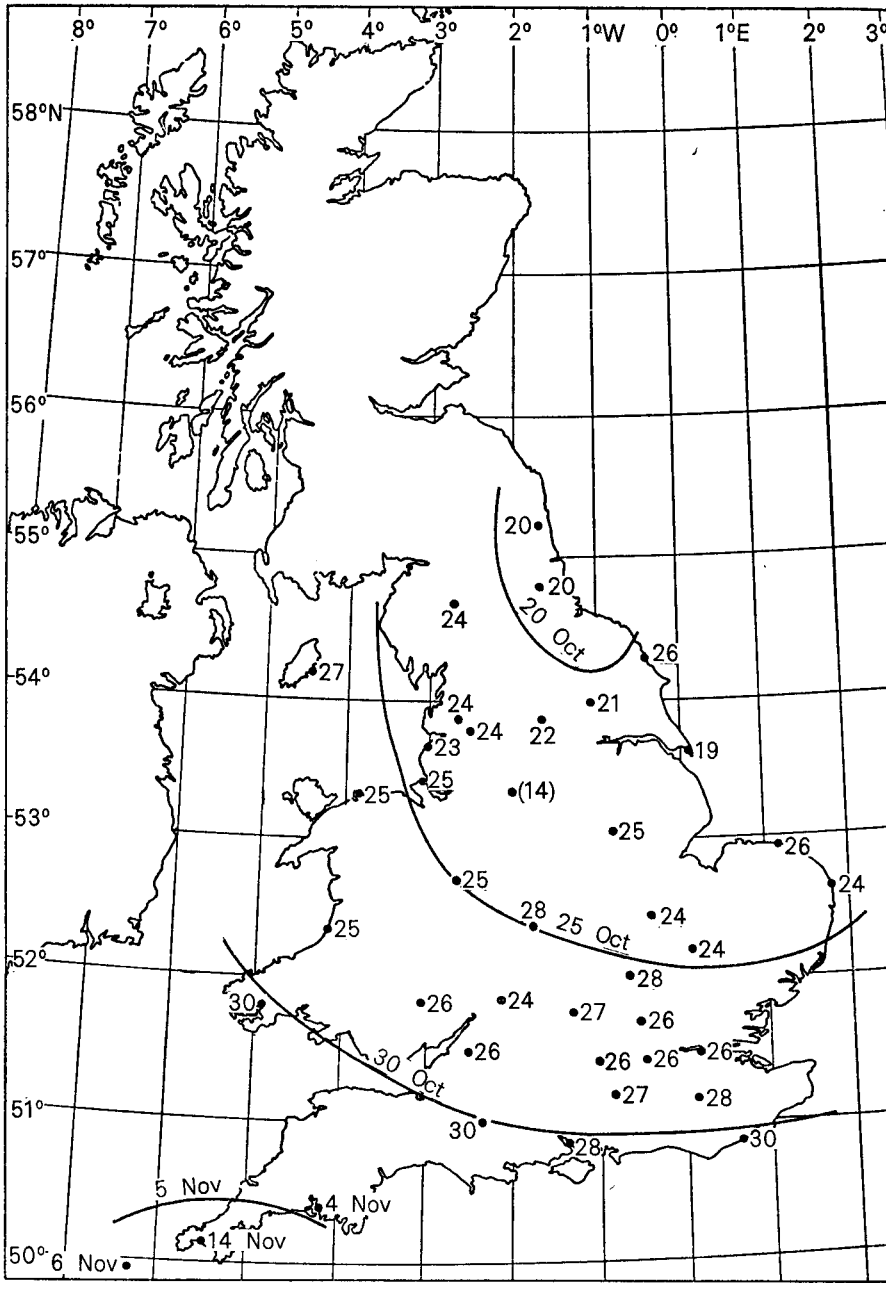

FIGURE 19—MEAN THIRD EARLIEST DATE OF FIRST COLD SNAP OF AUTUMN (REDUCED TO SEA LEVEL) IN THE PERIOD 1921–70

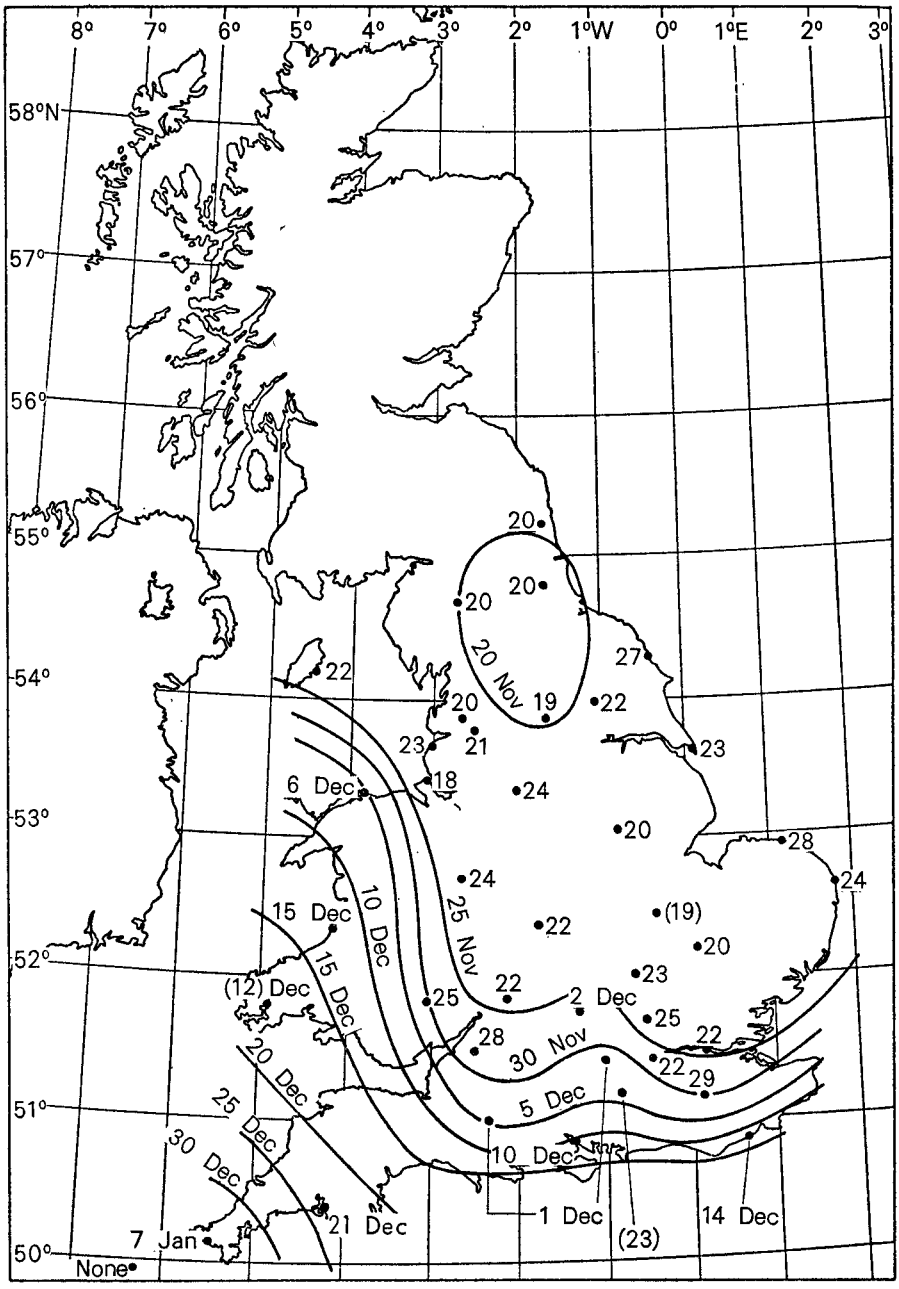

FIGURE 20—MEAN THIRD LATEST DATE OF FIRST COLD SNAP OF AUTUMN (REDUCED TO SEA LEVEL) IN THE PERIOD 1921–70

FORECASTING THE DATE

Over the four-year period 1970 to 1973, an attempt was made to forecast the date of the first cold snap at Oxford by using the methods of long-range forecasting that were used in making some experimental forecasts for autumn based on certain aspects of the weather during the summer. These forecasts were made on 1 September with the following results:

	Forecast	Actual
1970	9 November	13 November
1971	7 November	10 November
1972	14 November	16 November
1973	13 November	21 November

For the 50-year period 1921–70, average dates fall between 5 and 9 November, late dates between 10 and 14 November, and very late dates after 15 November. The predictions were for 2 average and 2 late dates against actuals of 2 late and 2 very late dates. In practice, further work would have to be done to update the forecasts on (say) 1 and 16 October and to make forecasts of the event 24 or 48 hours ahead. Methods of doing this have yet to be developed.

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BROOKS, C. E. P. and CARRUTHERS, N. 1953 Handbook of statistical methods in meteorology. London, HMSO.

DAVIS, N. E. 1972 Classified central England temperatures and England and Wales rainfall. *Met Mag*, **101**, pp. 205–217.

REVIEWS

Meteorology and Climatology (*Volume 1, Geophysics Series*), I. P. Danilova and A. P. Kapitsa (Scientific Editors). 235 mm × 165 mm, pp. i + 223, G. K. Hall & Co., 70 Lincoln Street, Boston, Mass., USA, 1975. Price: $29·00.

The Geophysical Department of VINITI, the All-Union Institute for Scientific and Technical Information, has planned to publish about every two years a set of volumes containing reviews on various aspects of Geophysics, Oceanology, Meteorology and Climatology, Physics of the Earth, Glaciology, Geomagnetism and the Upper Atmosphere. This volume is the first in the series on Meteorology and Climatology and the original Russian text was published in Moscow in 1971. It contains six major articles written by leading scientists and accordingly presents authoritative views on the state of these subjects both within and outside the USSR based on studies of world literature up to about 1970.

In the first section A.Kh. Khrgian briefly discusses recent developments in Physical Meteorology under the general headings of Textbooks on Meteorology,

Radiosondes, Dynamics and Macrophysics of Clouds, and Atmospheric Electricity. Although interesting and containing a useful large bibliography a more detailed and comprehensive treatment would have been welcomed in view of the large world-wide research effort devoted to different aspects of this subject in recent years. The second section written by K. Ya. Kondrat'yev on Satellite Meteorology contains a broad and quite detailed survey of the subject including Instruments carried by Weather Satellites, Interpretation of Television and Infra-red Pictures, the Earth's Thermal Budget, and Remote Sounding, backed by about 300 references. Even then the author notes that he has only been able to discuss the most important results in current work and the scientific literature actually discusses a much broader range of problems. The next section by the late B. L. Dzerdzeyevskiy is entitled 'Basic Problems of Climate Formation, Variability of Climate Regimes and Atmospheric–solar Relations'. This covers an enormous field and the author, again using a large number of references, has attempted to produce a comprehensive coverage. Consequently subjects which have attracted very considerable effort such as atmospheric pollution and weather modification are dealt with in a few pages and the impression is that the article will be of most use to workers in this general area who mostly need guidance to papers on recent work rather than an overall assessment of the subject. The same kind of comments may also be made about the next article on Agricultural Meteorology and Climatology by Yu. I. Chirkov and V. A. Shablevskaya. Here, however, the subject matter is more limited and specialized and no doubt the description of the extensive USSR effort in this important field will be of considerable interest to workers in other countries. The fifth section 'Photochemical Processes involved in the Generation of the Ozonosphere' by I. M. Kravchenko is rather different in concept, giving with comparatively few references an interesting account of the physical basis of this subject. Unfortunately it was written just before it became widely accepted that several minor constituents, particularly nitrogen oxides, considerably modify the ozone photochemistry and the large-scale studies of possible stratospheric ozone depletion due to aircraft operations and chemical releases at the surface were started. The later developments are certainly well known to the USSR workers and the apparent limitations of this article are of course a penalty of the time interval between its preparation and its general availability in the English language. The final article 'Climatic Existence Conditions for Glaciers and the Shaping of Glacial Climates' by A. N. Krenke deals comprehensively with most aspects of this subject, contains about 200 references, and appears to be a very useful contribution for specialists in this field.

In summary this volume although somewhat uneven in its treatment of the various subjects presents a valuable collection of articles and provides connected accounts of achievements both within and outside the USSR. In general its most important feature is the direction within the different articles to their sources of information and it seems likely that its main value will be in this aspect rather than in an attempt to obtain an assessment from it of the current status of a subject. Its application to current studies suffers considerably from the delay since its first appearance in the USSR but it and subsequent numbers in the series should certainly be acquired by libraries for the use of specialists and students attempting to gain an overall view of world-wide efforts in their field.

R. J. MURGATROYD

Noctilucent clouds, by V. A. Bronshten and N. I. Grishin. 240 mm × 170 mm, pp. v + 237, *illus.* (translated from the Russian by Israel Program for Scientific Translations, Jerusalem), John Wiley and Sons Ltd, Baffins Lane, Chichester, Sussex, 1976. Price: £13·20.

It will not be necessary to remind meteorologists that noctilucent clouds are those curiously high clouds (at approximately 80 km altitude) that can be seen from Scotland and other high-latitude places on many midsummer nights. First recognized as unusual in 1885 (the Krakatoa eruption was in 1883 and may or may not have caused particularly bright clouds to appear in subsequent years), the morphology and nature of the clouds is not yet clear. This book surveys in great detail nearly 70 years of observation, analysis and speculation. Much of the observational work has been carried out in the USSR with the inspiration, and under the supervision of, the authors. Noctilucent cloud studies here in the British Isles were for many years co-ordinated by the late James Paton and it is welcome news that they are to continue, with the guidance of Dr McIntosh of the Meteorology Department, Edinburgh University.

The volume under review continues the successful series of translations by the Israel Program for Scientific Translations. However, it has to be said that the English text appears not to have been read through by a meteorologist, or an upper-atmosphere physicist, to make the translation a little freer, perhaps a little more colloquial. It would then read better and some mistakes might have been avoided. For example, Jesse (1896) claimed an uncertainty of ±0·009 km for the mean of his height measurements, not 0·09; the legend to Figure 6 should refer to 'smoothed' rather than to 'flattened' curves; one has 'square degrees' rather than 'quadratic degrees' (the Russian word is *kvadratnyy*); aluminium is 'evaporated' not 'pulverized' (from *pul'verizatsiya*) in shadowing specimens for electron microscopy; Venus occults the star Regulus, Regulus does not cover Venus. But none of these does more than pull the reader up by the use of inappropriate words. In a few places the meaning is changed in the translation; e.g. *'ili zhe imelis neskol'ko otdel'nikh oblachnikh polei, razdelennikh promezhutkami'* seems to me to be 'or else had several separate cloud areas, with intervening gaps' rather than 'or compressed cloud fields separated by intervals'; *'togda kak do polynochi'* is surely 'while up to midnight' not 'while after midnight'?

Almost six hundred references are listed in the bibliography and the presence of these, tied to critical discussion in the text, alone almost fully justifies the efforts of Bronshten and Grishin. Were I to have been involved in the translation, I would have improved the book by compiling author and subject indexes; without them, it is difficult to refer quickly to a particular topic.

There is now increasing interest in the behaviour of the upper atmosphere and in relationships between solar activity and climate or weather. Noctilucent clouds provide a visible indicator of conditions in the high atmosphere; their study will grow in importance and popularity in the next few years. The research worker and the student, the meteorologist and the layman, can all rely on this textbook keeping its place for many years, as it has for six years already in the Russian text.

M. GADSDEN

NOTES AND NEWS

Election of Dr B. J. Mason to the Presidency of the Institute of Physics

Dr B. J. Mason, C.B., F.R.S., the Director-General of the Meteorological Office, has been elected President of the Institute of Physics for a two-year term beginning on 1 October 1976. He succeeds Professor Sir Brian Pippard. The Institute has more than 16 000 members, holds about 60 major meetings each year, publishes journals to the value of more than £1 million per annum, and is responsible for the Fulmer Research Institute which undertakes commissioned research.

Symposium on Meteorological Services (other than weather forecasting) for Water Management

A Symposium on 'Meteorological Services (other than weather forecasting) for Water Management' was held at the Meteorological Office College, Shinfield Park, Reading on 24 March 1976. The Symposium was opened by Dr B. J. Mason, C.B., F.R.S., Director-General, Meteorological Office and was chaired by Mr J. K. Bannon, I.S.O., Director of Services. An invited audience represented many organizations interested in water, such as the Regional Water Authorities of England and Wales, the Central Water Planning Unit, the Water Data Unit, the Hydraulics Research Unit, the Water Research Centre, the Institute of Hydrology, the Greater London Council, the Department of the Environment, the Ministry of Agriculture, Fisheries and Food and a number of engineering firms.

There were four papers, namely 'Handling hydrometeorological data' by R. J. Shearman, 'Answering enquiries on rainfall, evaporation and soil moisture deficit' by B. G. Wales-Smith, 'Rainfall analysis and snow studies for drainage design' by J. F. Keers and 'Measurement of meteorological elements of interest to water management' by Dr T. W. Harrold.

A slightly shortened version of the Shinfield Park Symposium was held at Edinburgh on 13 May 1976 and attended by nearly 50 hydrologists and engineers. Mr W. G. Harper, Superintendent, Meteorological Office, Edinburgh chaired the Symposium and Mr J. F. Keers and Mr B. G. Wales-Smith covered the work which was dealt with in the first three talks given at the Shinfield Park Symposium in March 1976.

At both symposia each talk was followed by a lively and informative discussion. It was clear that many participants had not hitherto been aware of the variety of hydrometeorological services available from the Meteorological Office. The flow of information was two-way, and the Office found out a good deal about the problems and requirements of the various organizations which have an interest in operational hydrology and engineering.

The spelling of 'program'

Some readers have expressed concern that the *Meteorological Magazine* should have adopted what they describe as the American way of spelling as 'program' the word that they are generally used to seeing spelt in British publications—except perhaps when it refers to computers—as 'programme'. This shorter spelling, however, is not exclusively modern American in origin but is also traditional English and was employed from the first recorded use of the word in the early 17th century until a French way of spelling it began to be adopted in the 19th; some leading writers, e.g. Scott, Carlyle, Browning and Shaw, resolutely maintained the old spelling.

'Program' is consistent in its spelling with all other English words incorporating the same Greek root, e.g. telegram, monogram, diagram etc., and is the first and preferred spelling in the 'Shorter Oxford English Dictionary'.

EDITOR

OBITUARY

It is with regret that we have to record the death on 2 June 1976 of Mr A. W. E. Barber, Higher Scientific Officer, Met.O.7.

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It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked 'For Meteorological Magazine'.

The responsibility for facts and opinions expressed in the signed articles and letters published in this magazine rests with their respective authors.

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VARIATIONS IN GLOBAL SOLAR RADIATION AT KEW

By J. P. COWLEY

SUMMARY

Global solar radiation data recorded at Kew since 1951 were used to establish changes in the global irradiance at the earth's surface in the absence of clouds. To do this, a characteristic value, the Global Solar Radiation Index, was obtained for each month; the series of values forms a consistent set and the use of such an index is thus justified. Numerical filtering techniques were used to establish seasonal and secular trends in the data. It is suggested that changes found in the winter months are associated primarily with changes in fuel technology, supported by legislation controlling the emission of pollutants into the atmosphere. Variations in the summer months were much less; they form the basis of a separate study.

INTRODUCTION

Interest is currently being expressed in changes in the climate of the British Isles. Solar radiation records do not go back far enough for climatic trends in solar radiation to be postulated directly from data. There is, however, a record of hourly average values of the intensity of global solar radiation in the wavelength band of 0·3 to 3·0 micrometres measured at Kew (51° 28′N, 0° 19′W) near London, which began in January 1947, but was of questionable quality before 1951.

An investigation was mounted to establish any trends in global solar radiation at Kew under clear skies since 1951. Any such trends would result from changes in the emphasis to be given to the mechanisms by which solar radiation is scattered and absorbed in passing through the earth's atmosphere. Scattering may be by gaseous molecules (Rayleigh scattering) or by aerosols (Mie scattering). Molecular absorption of solar radiation takes place for certain well-defined frequencies, corresponding to permitted energy transitions within the molecules; atmospheric ozone absorbs the majority of solar ultra-violet radiation incident on the atmosphere, for instance. Atmospheric aerosols also absorb solar radiation, but in a less well-defined manner. The solar radiation reaching the earth's surface would be expected to change significantly both with aerosol content, which may be a function of wind direction, and with the atmospheric water vapour content.

Evans (1957), Brazell (1964), Wiggett (1964) and Jenkins (1969) discuss the decrease in fog occurrences in the London area (and the increase in the duration of bright sunshine) and associate this with the decrease in air pollution. Improvements in the efficiency of fuel burning and change of fuel types, together with successive legislative enactments in 1954, 1956, 1968 and 1971 to restrict the emission of smoke, and later sulphur, from buildings of all kinds, might be expected to result in increases in the measured solar radiation at Kew over this period.

A parameter, the Global Solar Radiation Index, referred to later as the GSRI, was introduced in this work to characterize the global solar radiation that would be expected during any one hour in which the sky was entirely clear.

The sequence of GSRIs was examined for the period from 1951 to 1974 for correlation from month to month and from year to year. Results indicated that a systematic pattern was present together with some fluctuations. It was possible to use the time-series of these indices, by applying low-pass filtering techniques, to demonstrate the trend in GSRI at Kew.

A change in GSRI might be attributed to a number of causes, including

(i) variation in atmospheric scattering or absorbing processes,

(ii) variation in the solar radiation in the wavelength range 0·3–3·0 micrometres incident on the atmosphere, and

(iii) variation in instrument response, or in the reference standard etc.

Careful attention has been paid to the standardization of radiation measurements made at Meteorological Office stations. It is claimed that individual measurements of global solar radiation are subject to two main errors: a zero-shift of less than ± 5 W/m^2 and an instrument calibration error that is less than ± 5 per cent of the value indicated. No significant changes in reference standards have been found at international pyrheliometric comparison meetings. Consequently, it is suggested that (iii) has not been a significant factor in the results obtained.

No evidence is offered to suggest that there have been changes in the solar constant (cf. (ii)). The inference here is that the significant changes found over the period from 1951 onwards are to be associated with changes in levels of atmospheric pollution and the attendant scattering processes.

Measurements

Two types of measurement were used in this study: hourly averaged global solar irradiance on a horizontal surface and duration of bright sunshine.

The former is continuously monitored by Moll–Gorczynski pyranometers. These instruments are recalibrated every two years against the United Kingdom reference standard at the National Radiation Centre, Beaufort Park, Bracknell. The sensor is a thermopile in thermal contact with a copper plate across which a thermal gradient is created by the absorption of solar radiation by the optically black upper surface. The electromotive force developed by the thermopile is proportional to the irradiance and is automatically logged. Data were initially extracted manually from chart records but since the early 1960s the data have been recorded by MODLE Mk I equipment on computer-compatible tape (MODLE is an acronym for 'Meteorological Office Data Logging Equipment'). This device is shortly to be replaced by MODLE Mk III which will record on to magnetic tape in a cartridge. MODLE data are transcribed later to archive magnetic tapes.

Data concerning the duration of bright sunshine are added to the archive tapes after manual interpretation of Campbell–Stokes sunshine recorder cards.

Global solar radiation index (GSRI)

Within any given month, this was defined as the average global solar radiation ($\overline{G}$) measured over a one-hour interval for which there was a complete hour of bright sunshine, divided by the global solar radiation (G_0) that would have been measured outside the atmosphere over the same interval; it is thus a pure number.

The normalization factor G_0 was calculated from the solar elevation (a), the solar constant (I_0) (assumed invariant, and taken in this work to be 1353 W/m^2), and the eccentricity of the earth's orbit. We may write

$$G_0 = I_0 \sin a\,(1 + 0.03345 \cos 2\pi \{\text{day } (n)/365\}),$$

where day (n) was the day-number of the day on which measurement was made (on 3 January, $n = 1$). The correction for the non-circularity of the earth's orbit gives results within 0·03 per cent of those quoted by Robinson (1966).

The GSRI could have been arrived at simply as the average of the normalized measurements of global solar radiation corresponding to 1·0 hour's bright sunshine in a given month, as recorded by a Campbell–Stokes sunshine recorder. A regression approach was used, however, so that values of radiation corresponding to less than one hour of bright sunshine could be used to improve the accuracy of the estimation.

When correlating hourly data, it is assumed that the normalized global radiation may be related to the fractional duration of bright sunshine, F_s, by the equation

$$G = \sum_{n=0}^{N} a_n (F_s)^n,$$

where a_n are coefficients.

In previous work (Day, 1961) the regression fit for $N = 1$ was used when correlating daily totals, but it was found that this linear relationship was not adequate for hourly data. The above equation was repeatedly applied to the data for $N = 1$ to $N = 5$, each solution of the coefficient values being that which gave the minimum sum of the squares of the data values about the polynomial. The improvement (decrease) in standard deviation of data about these regression equations, averaged for each calendar month of the 24 years, is shown in Figure 1. For each month there is substantial improvement up to the third-order regression, i.e. for $N = 3$, but thereafter the improvement is slight. This may be explained on physical grounds.

Figure 2 shows for a typical month the association between hourly values of normalized global solar radiation at the earth's surface and bright-sunshine duration during the hour (range 0–1 hour). It is clear that a linear relationship describes the relation well for bright-sunshine values over the greater part of the range. Departures from a linear fit are evident at the extremes of little or no sunshine during the hour and a mostly sunny hour. An explanation offered here is that if there is some bright sunshine in a given hour, the cloud cover is typically broken and not usually multi-layered; in the absence of bright sunshine the cloud cover is more likely to be multi-layered, with consequential increased scattering and attenuation of the incoming solar radiation. Stagg

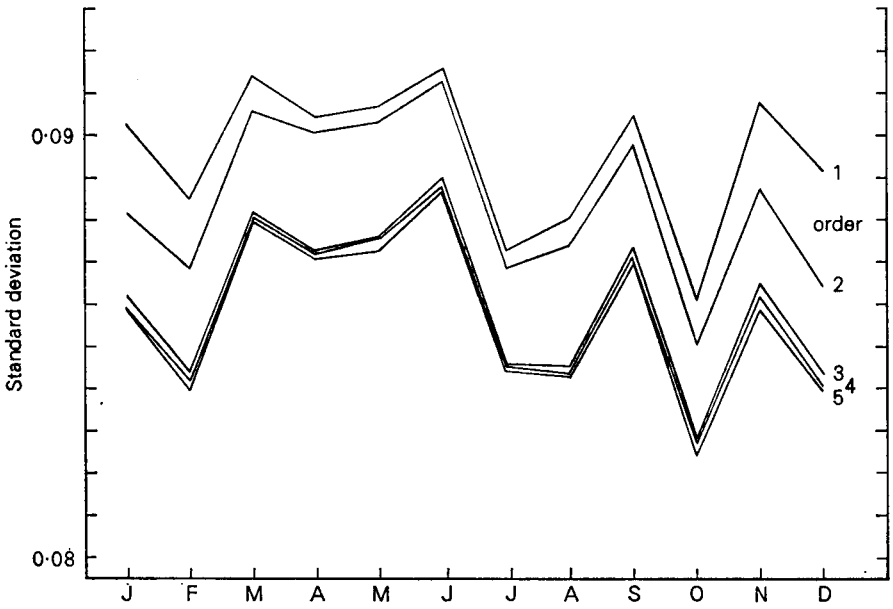

FIGURE 1—STANDARD DEVIATIONS OF NORMALIZED GLOBAL RADIATION ABOUT REGRESSION FITS OF ORDER 1 TO 5 BASED ON DATA FOR 1951–74

(1950) reported sunshine records to be systematically overestimated for periods of intermittent sunshine. As a consequence, in this situation, a particular radiation value is to be associated with too high an estimated (recorded) value of sunshine duration, as shown in Figure 3. Points A, B refer to recorded values and A′, B′ to true values. The effects of multi-layered cloud and systematic errors in reading from sunshine cards would combine to produce a quasi-cubic relationship between global solar radiation and the duration of bright sunshine.

Values of the GSRI for Kew for the period 1951–74, together with the standard deviations about the GSRI of the normalized global solar radiation values corresponding to 1·0 hour's bright sunshine, are given in Table I.

Reference was made to the reliability codes of the archived radiation values; only those quoted as being reliable were used.

In spite of these particular precautions it was still possible for poor or inadequate data to be included in the analysis. The seasonal accuracy of the standard deviation of the GSRI for each month is shown in Figure 4. Here the standard deviation is that of the data corresponding to a whole hour of bright sunshine about the GSRI (in Figure 1 the standard deviations are for all data about the regression solutions). The variation is largely explained by the number of hours of daylight in each month. Winter-month estimates of GSRI are also poorer because of the lower frequency of hours of 1·0 hour's bright-sunshine duration. The criterion was adopted that, if the standard deviation of the estimate for a given month exceeded 0·02, then the GSRI value was not used in further analysis. The assumptions here were that there had either been considerable instrumental difficulties or that there had been significant archiving errors.

LOW-PASS FILTERING TO INVESTIGATE THE SECULAR TREND IN 'GSRI'

A digital filter (a linear combination of unitary filters that were designed by Craddock (1968)) was used. It had the following characteristics:

(i) forty-one consecutive equally-spaced point values are required for each filtered value which is assigned to the 21st point in that sequence;
(ii) zero phase-change is introduced in those periodicities that are passed;
(iii) periodicities of <15 time-intervals are removed;
(iv) periodicities of >30 time-intervals are unattenuated.

When the filter is applied to the time-series of GSRI values, seasonal variations are removed but secular changes are retained. It was possible to secure a substantial reduction in the effect of periodicities of less than five years by applying a five-year running mean to the GSRIs for each calendar month through the analysis period before applying the compound unitary filter.

The transfer characteristics of the low-pass filter, both with and without the five-year running mean, are shown in Figure 5. The maximum amplitude of a sinusoidal signal

$$G = \sin(2\pi t/\tau)$$

over a 25-year period is plotted as a function of the periodicity τ.

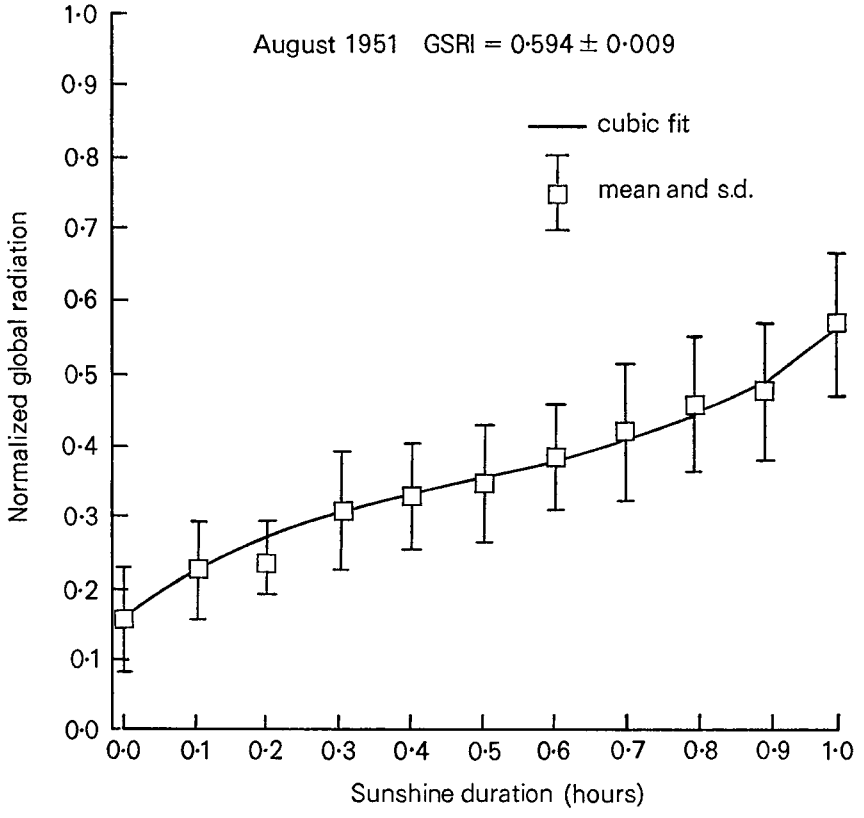

FIGURE 2—TYPICAL ASSOCIATION BETWEEN NORMALIZED GLOBAL RADIATION DATA AND SUNSHINE DURATION

The GSRI for August 1951 should read 0·574±0·009.

TABLE I—MONTHLY VALUES OF GLOBAL SOLAR RADIATION INDEX (GSRI) AND STANDARD DEVIATION (S.D.) OF NORMALIZED GLOBAL SOLAR RADIATION VALUES CORRESPONDING TO 1·0 HOUR'S BRIGHT SUNSHINE ABOUT THE GSRI

	JAN		FEB		MAR		APR		MAY		JUNE		JULY		AUG		SEPT		OCT		NOV		DEC	
	GSRI	S.D.	GSRI	S.D.	GSRI	S.D.	GSRI	S.D.	GSRI	S.D.	GSRI	S.D.	GSRI	S.D.	GSRI	S.D.	GSRI	S.D.	GSRI	S.D.	GSRI	S.D.	GSRI	S.D.
1951	0·511	0·022	0·566	0·021	0·601	0·016	0·585	0·008	0·609	0·011	0·618	0·008	0·594	0·008	0·574	0·009	0·559	0·012	0·504	0·011	0·448	0·017	0·454	0·015
1952	0·487	0·014	0·497	0·012	0·604	0·013	0·577	0·009	0·596	0·009	0·604	0·009	0·587	0·010	0·619	0·010	0·587	0·013	0·547	0·015	0·532	0·016	0·505	0·017
1953	0·445	0·018	0·536	0·016	0·496	0·011	0·578	0·010	0·635	0·008	0·602	0·009	0·677	0·012	0·613	0·009	0·618	0·010	0·561	0·014	0·528	0·015	0·494	0·018
1954	0·516	0·017	0·539	0·022	0·573	0·013	0·573	0·010	0·629	0·011	0·642	0·011	0·663	0·011	0·633	0·011	0·638	0·011	0·591	0·014	0·631	0·016	0·576	0·015
1955	0·508	0·021	0·596	0·017	0·569	0·010	0·643	0·008	0·651	0·008	0·631	0·010	0·617	0·007	0·595	0·007	0·595	0·010	0·583	0·012	0·463	0·022	0·516	0·019
1956	0·533	0·017	0·465	0·021	0·593	0·010	0·603	0·010	0·634	0·006	0·643	0·011	0·649	0·009	0·650	0·009	0·572	0·011	0·572	0·010	0·535	0·014	0·518	0·037
1957	0·483	0·016	0·543	0·011	0·581	0·011	0·596	0·008	0·634	0·007	0·609	0·006	0·584	0·011	0·597	0·009	0·612	0·017	0·550	0·013	0·527	0·013	0·470	0·019
1958	0·561	0·020	0·531	0·016	0·582	0·014	0·604	0·009	0·625	0·008	0·595	0·012	0·569	0·008	0·656	0·015	0·602	0·012	0·597	0·013	0·509	0·019	0·471	0·020
1959	0·448	0·013	0·512	0·013	0·574	0·012	0·567	0·010	0·622	0·008	0·635	0·007	0·603	0·007	0·605	0·007	0·571	0·006	0·571	0·007	0·533	0·020	0·520	0·020
1960	0·480	0·020	0·559	0·012	0·571	0·013	0·613	0·009	0·608	0·008	0·596	0·007	0·638	0·014	0·618	0·011	0·599	0·009	0·567	0·017	0·581	0·015	0·518	0·013
1961	0·492	0·018	0·566	0·012	0·628	0·008	0·605	0·013	0·617	0·007	0·628	0·007	0·617	0·008	0·632	0·009	0·610	0·011	0·596	0·010	0·589	0·014	0·509	0·014
1962	0·567	0·014	0·580	0·016	0·581	0·013	0·652	0·011	0·659	0·009	0·668	0·006	0·651	0·013	0·674	0·009	0·652	0·010	0·586	0·009	0·615	0·022	0·520	0·014
1963	0·525	0·022	0·550	0·013	0·624	0·011	0·656	0·010	0·646	0·008	0·653	0·007	0·617	0·008	0·599	0·011	0·628	0·009	0·610	0·010	0·557	0·018	0·465	0·016
1964	0·521	0·017	0·559	0·014	0·638	0·014	0·662	0·012	0·656	0·007	0·640	0·010	0·644	0·007	0·647	0·007	0·640	0·006	0·610	0·010	0·543	0·016	0·516	0·116
1965	0·520	0·018	0·604	0·029	0·656	0·010	0·641	0·016	0·694	0·011	0·708	0·010	0·666	0·012	0·641	0·009	0·656	0·011	0·581	0·008	0·577	0·011	0·554	0·013
1966	0·544	0·018	0·624	0·044	0·647	0·010	0·661	0·011	0·671	0·008	0·656	0·008	0·649	0·010	0·642	0·008	0·625	0·009	0·611	0·016	0·568	0·029	0·542	0·020
1967	0·549	0·026	0·601	0·012	0·644	0·009	0·634	0·013	0·629	0·010	0·658	0·008	0·635	0·007	0·643	0·008	0·617	0·012	0·646	0·010	0·525	0·015	0·549	0·020
1968	0·529	0·023	0·578	0·014	0·658	0·012	0·621	0·007	0·623	0·009	0·645	0·010	0·629	0·011	0·616	0·011	0·611	0·018	0·640	0·015	0·560	0·019	0·526	0·027
1969	0·593	0·023	0·646	0·016	0·611	0·012	0·635	0·007	0·635	0·010	0·633	0·012	0·646	0·007	0·628	0·010	0·642	0·011	0·601	0·009	0·599	0·014	0·541	0·027
1970	0·578	0·020	0·604	0·013	0·599	0·014	0·634	0·012	0·647	0·007	0·636	0·006	0·639	0·009	0·565	0·011	0·639	0·008	0·620	0·011	0·608	0·016	0·558	0·027
1971	0·560	0·024	0·597	0·016	0·635	0·013	0·640	0·010	0·630	0·007	0·671	0·010	0·630	0·006	0·613	0·010	0·619	0·007	0·639	0·007	0·593	0·009	0·593	0·025
1972	0·579	0·019	0·688	0·026	0·620	0·009	0·651	0·009	0·657	0·011	0·647	0·010	0·645	0·008	0·601	0·007	0·589	0·012	0·614	0·009	0·612	0·011	0·556	0·017
1973	0·610	0·021	0·611	0·013	0·614	0·011	0·647	0·011	0·666	0·010	0·661	0·006	0·646	0·009	0·617	0·007	0·623	0·010	0·628	0·013	0·596	0·012	0·582	0·016
1974	0·634	0·018	0·638	0·014	0·660	0·010	0·617	0·008	0·667	0·009	0·652	0·007	0·648	0·008	0·629	0·008	0·667	0·008	0·633	0·013	0·637	0·024	0·593	0·014

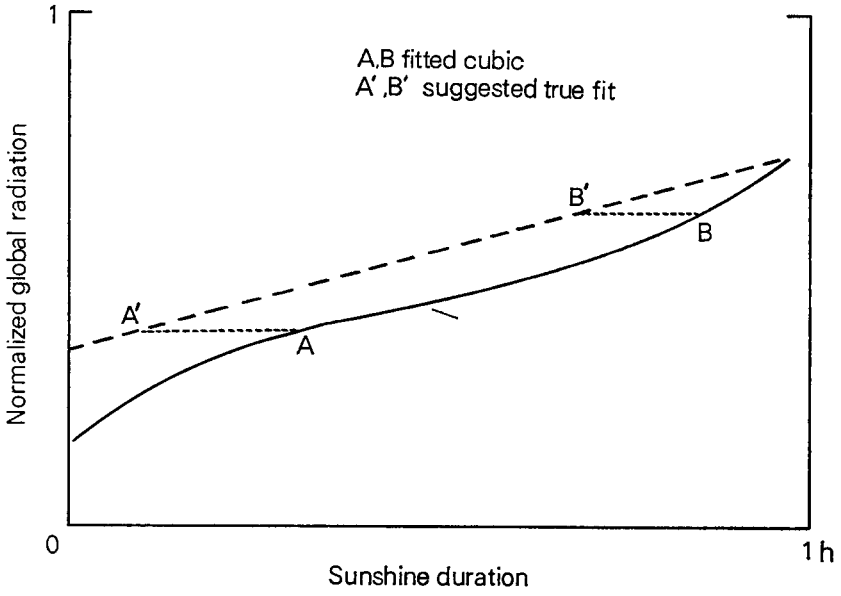

FIGURE 3—DEVIATION FROM LINEAR RELATIONSHIP BETWEEN NORMALIZED GLOBAL RADIATION AND SUNSHINE DURATION IN THE RANGE 0–1 HOUR

Both the unfiltered and the filtered time-series of GSRIs including and excluding the five-year running mean are shown in Figure 6. The low-pass digital filter has clearly been effective in removing the seasonal component in the GSRI time-series; the five-year running mean was needed to indicate long-term trends in GSRI because periodicities of about two years, which would otherwise be present in the filtered values, are not significant when considering trends over a period of 24 years.

The principal features of the trend as given by filtering the five-year running-mean values of GSRI are:

(i) a maximum in 1956, falling rapidly to
(ii) a minimum in 1958, followed by
(iii) a steady rise between 1959 and 1964, and
(iv) an approximately constant value from 1964 to the beginning of 1970.

(1970 marks the end of the period after truncation of the time-series resulting from the smoothing processes.)

Separation of seasonal and secular effects

It is seen from Figure 6 that the amplitude of the seasonal component of the basic GSRI time-series changed during the period considered. The change in seasonal pattern, as well as the secular trend, can be observed by constructing a GSRI diagram in which the individual monthly values are plotted orthogonally to the year-axis as in the coarsely contoured Figure 7. It can be seen

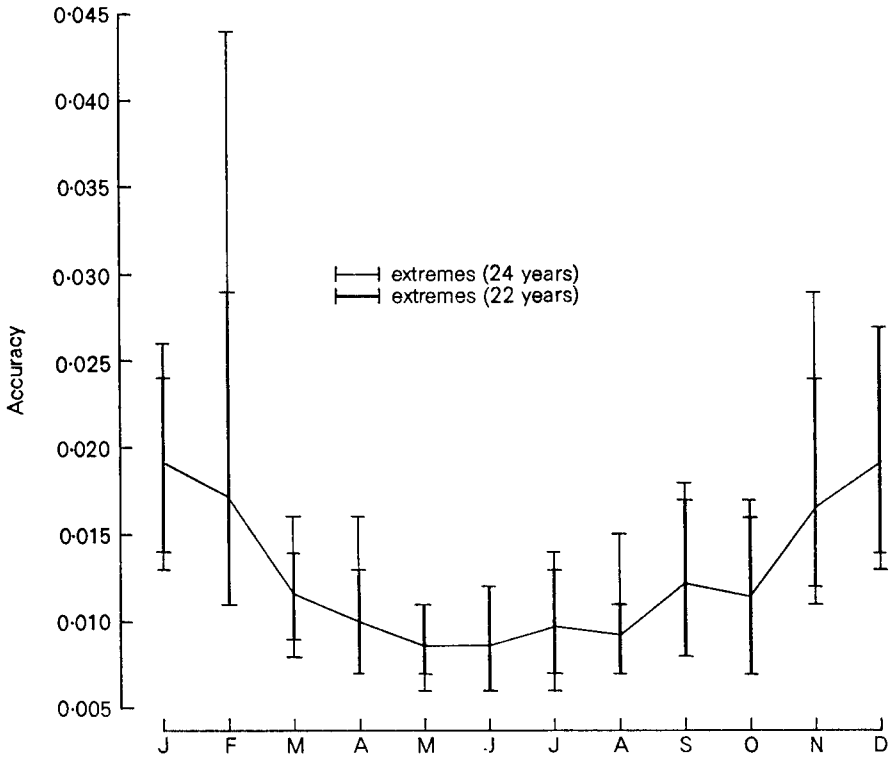

FIGURE 4—SEASONAL DEPENDENCE OF ACCURACY OF STANDARD DEVIATION OF 'GSRI' DATA ABOUT CUBIC SOLUTION

$$\text{Accuracy} = \frac{\text{Standard deviation of all data about cubic}}{(\text{Number of hours with 1.0 h bright sunshine})^{\frac{1}{2}}}$$

that, as the years progress, the 0·60 isopleth comes closer to the start and end of the year, corresponding to the improvement (increase) in winter-time values of GSRI.

Any section through the diagram parallel to the year-axis would indicate how the GSRI value for a particular month changed from 1951 to 1974.

It should be noted that values interpolated between the grid points do not have any significance.

Filtering the 'GSRI' diagram

It was useful to emphasize trends in both seasonal and secular patterns by applying a filter to the GSRI diagrams described above to remove 'high-frequency' components from the data field. This was achieved by fitting, by least-squares approximation, an eighth-order polynomial. The resulting smoothed field is shown in Figure 8. Phase changes may be introduced by this filter, but trends are shown clearly; the secular changes for January and July are shown in Figure 9.

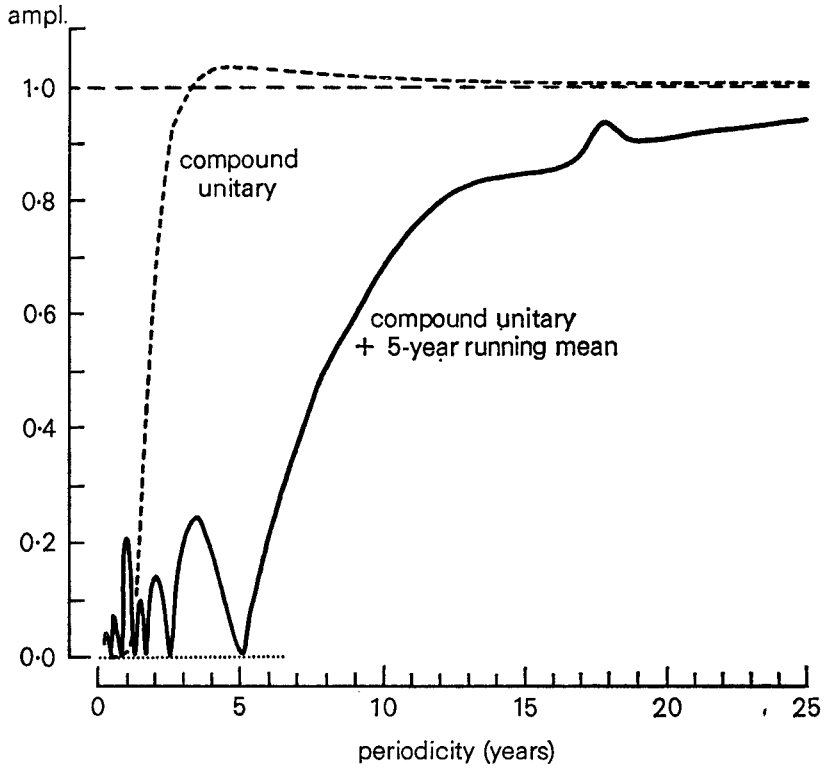

FIGURE 5—TRANSFER CHARACTERISTICS OF FILTERS
'ampl.' = amplitude of output for unit sinusoidal input.

Discussion

It is evident from Figure 9 that the winter-time value has changed over the period from 1951 to 1974 by about 25 per cent (from 0·46 in 1951 to 0·58 in 1974). Jenkins (1969) investigated the change in the duration of bright sunshine at London Weather Centre, Kew and Wisley, and his Figure 1 shows that since 1958 sunshine has increased by 17 per cent during the months from November to January, when compared with the long-term averages for the period 1931–60. He associated this increase with the Clean Air Act and its effect on both locally generated and advected atmospheric pollution. Lawrence (1969) showed that changes in smoke concentration at Kew were associated with surface winds from the direction of London (to the east) rather than from nearby buildings to the south-west. The change from the pre-sixties winter-time values to early-sixties values is about half that recorded over the total period from 1951 to 1974, that is to say about 13 per cent. This is of a similar order of magnitude to the finding of Jenkins.

The continued improvement in GSRI in the later sixties and to the present time may be associated with the change-over from solid fuel to oil and gas for domestic, commercial and industrial purposes, together with legislation limiting the emission of sulphur in London (1971). Auliciems and Burton (1973)

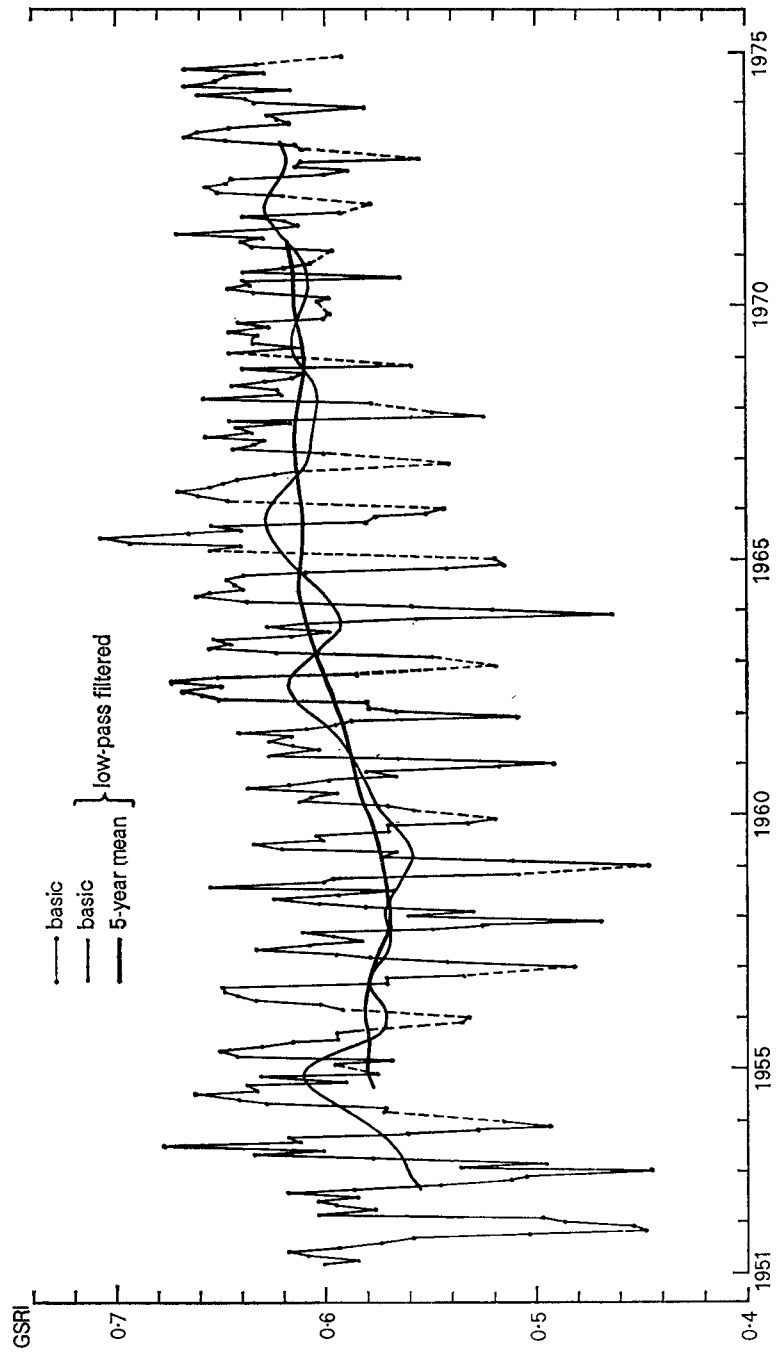

FIGURE 6—TIME-SERIES OF MONTHLY VALUES OF 'GSRI'
Dashed lines straddle doubtful monthly values.

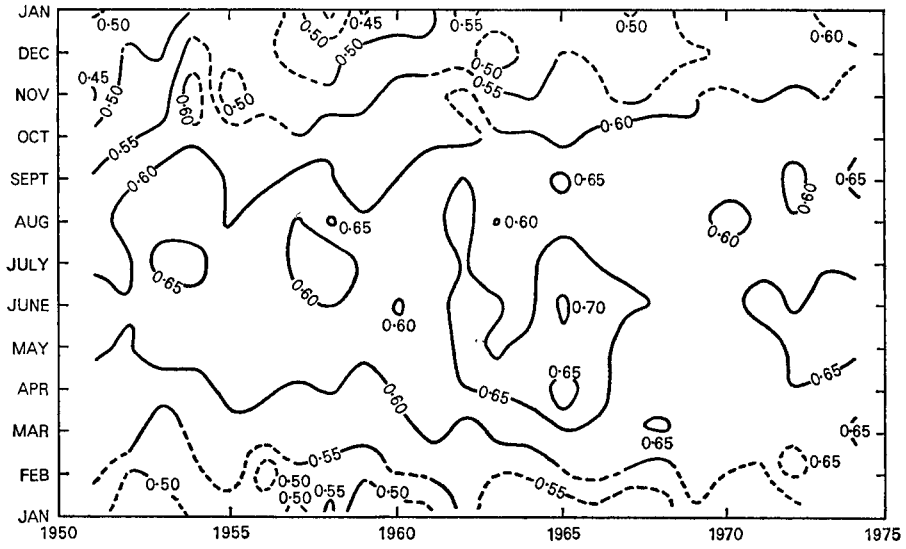

FIGURE 7—INTER- AND INTRA-ANNUAL VARIATION OF 'GSRI' VALUES

—— standard deviation of data <0·02
– – – standard deviation of data ≥0·02

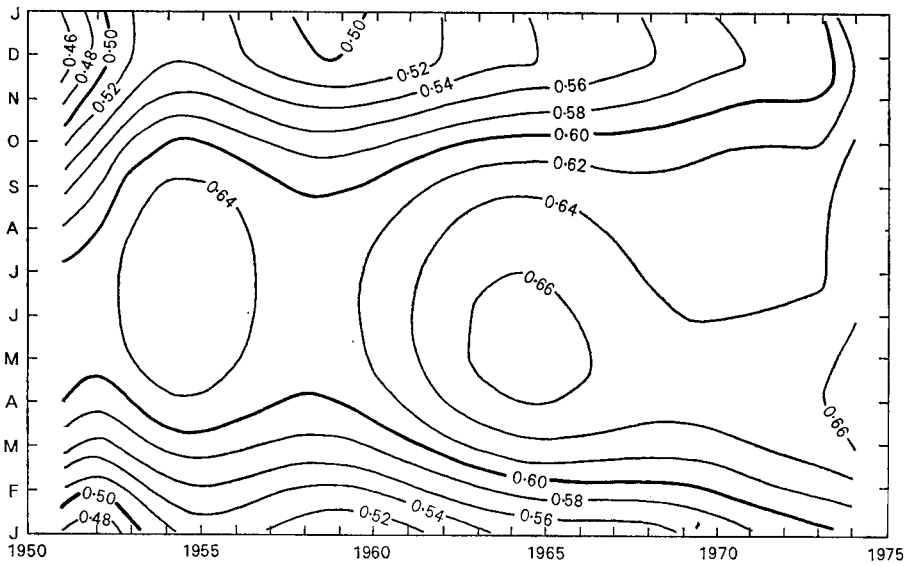

FIGURE 8—EIGHTH-ORDER POLYNOMIAL FITTING OF 'GSRI' DIAGRAM (FIGURE 7)

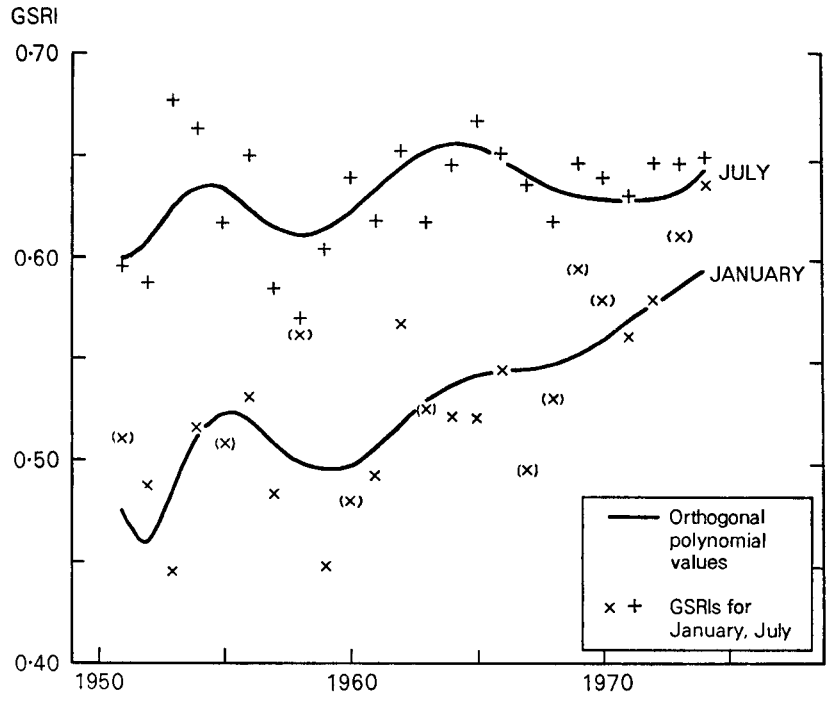

FIGURE 9—VARIATION OF 'GSRI' 1951–74

considered the smoke concentrations measured at Kew. Figure 10 shows the low-pass filtered time-series of smoke concentrations measured at Kew since 1926 plus the filtered time-series of GSRI for 1951–74. The present work supports their view that the reduction in smoke concentration is a consequence of technological improvements rather than of legislation. The scatter diagram and linear regression analysis of filtered GSRI values on smoke levels are shown in Figure 11. The correlation coefficient of −0.829 indicates that the former is strongly related, secularly, to the latter.

There was an 8 per cent change in GSRI in the summer between 1951 and 1964 but, as shown in Figure 7, this change was not monotonic and the GSRI is currently at the same level as in 1964. The difference in secular change in the summer when compared with the winter may be attributed largely to the change-over in fuel types, but the cause of the fluctuations in GSRI in the summer requires further study.

Figure 8 shows that the seasonal pattern has changed during the analysis period; the summer maximum has moved from June–July to May–June and a secondary maximum may be forming in August. Care must be taken in interpreting the filtered GSRI diagram; reference should always be made to the actual data to support identification of real features.

Conclusion

The seasonal and secular changes in global solar radiation under 'clear skies' have been shown to exist, and their magnitude has been calculated. It has

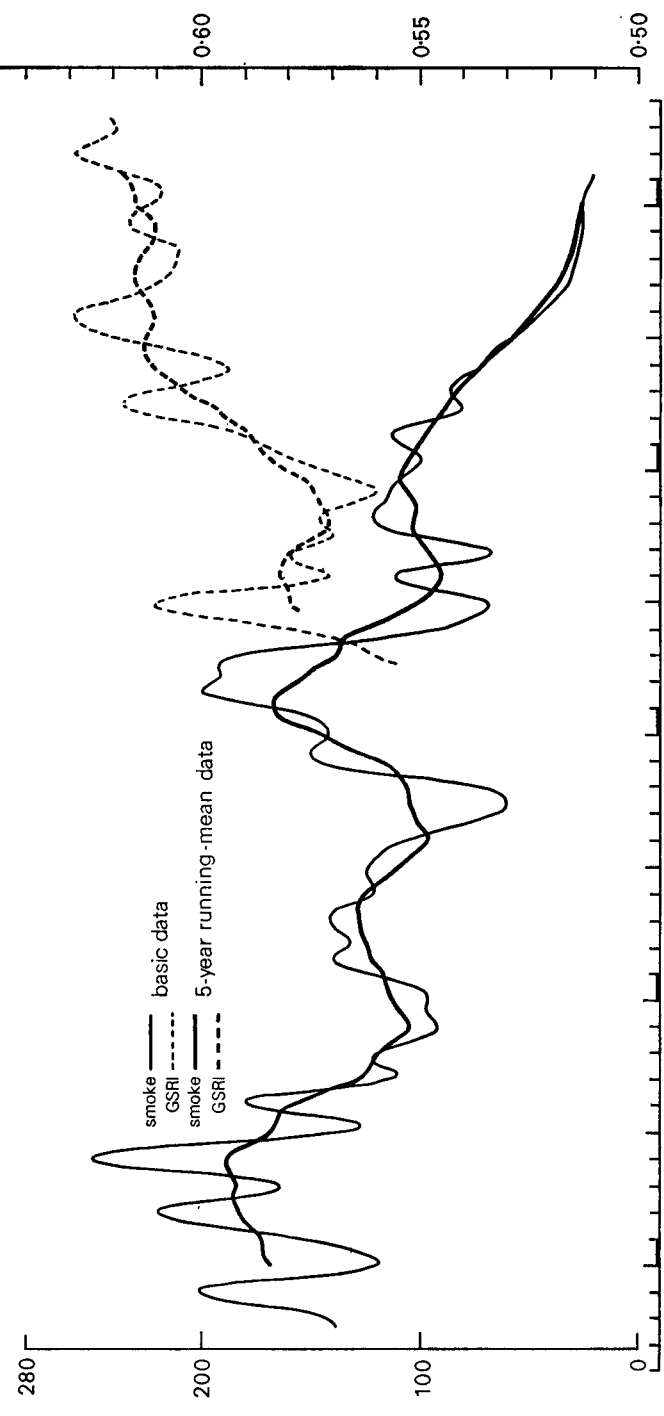

FIGURE 10—LOW-PASS FILTERED SMOKE CONCENTRATION (1926–73) AND 'GSRI' (1951–74) FOR KEW, USING FIVE-YEAR RUNNING-MEAN DATA AND BASIC DATA

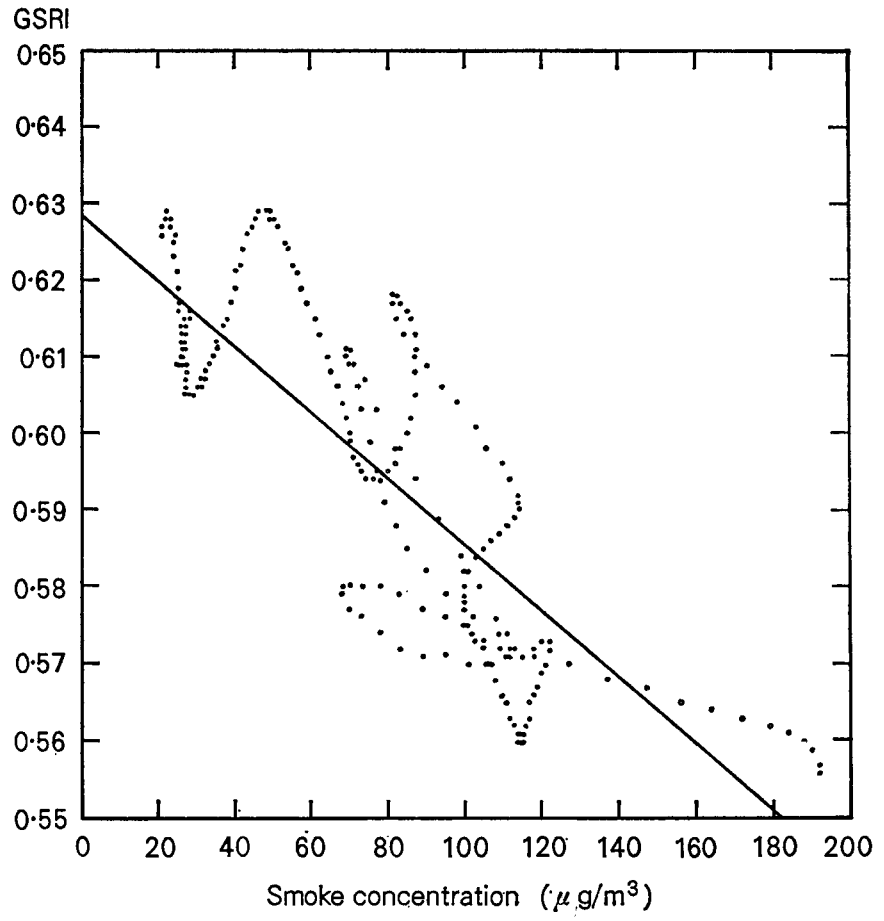

FIGURE 11—SCATTER DIAGRAM AND REGRESSION LINE OF 'GSRI' ON SMOKE CONCENTRATION

Correlation coefficient R = —0·829; slope = —0·430; constant = 0·629.

been found that there has been a change of 8 per cent in the summer in the GSRI and a 25 per cent change in the winter. There was a variation of ± 4 per cent over the period of a decade in summer values. Changes in GSRI are largely associated with the reduction in artificial contamination of the atmosphere over Kew, a process that has continued throughout the 24 years, associated both with the change in fuel types as technology has developed and also with the laws brought in to control smoke and sulphur emission.

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OPTIMUM AVERAGING TIME FOR REPORTS OF ALONG-RUNWAY AND ACROSS-RUNWAY WIND COMPONENTS TO AVIATION

By M. J. O. DUTTON

Summary

For selected occasions during a three-month winter period and a four-month summer period at London/Heathrow Airport winds averaged over intervals of time from 30 seconds to 10 minutes were compared with the 30-second means at later times, simulating the procedure whereby wind observations provided by Air Traffic Control are used by a pilot. A previous study looked only at the statistics of errors in the total vector wind. The results of this study of orthogonal components of the wind, along and across the runway direction, provided further confirmation that the ICAO-recommended 2-minute average wind adequately reduces the frequency of errors (in either component) of 10 knots or more, provided that the time lag between the supply of the wind report and its use is less than 5 minutes. The results for both components are broadly similar, although, for any given lag, errors of 10 knots or more in the across-runway component are on average about twice as frequent as those in the along-runway component.

Introduction

In two earlier studies, by Hardy (1974) and Dutton (1975), samples of turbulent wind conditions at Heathrow during summer 1973 and winter 1973–74 were analysed to determine what is the optimum averaging period to use for a wind report supplied to an aircraft pilot shortly before touchdown or take-off, for use as a forecast of the wind at touchdown or take-off. Both studies considered only the magnitude of the total *vector error* in the wind report and illustrated how the optimum averaging period not only varied with the lag between the supply of the report and its use, but was also dependent on the relative importance of errors of different magnitudes. Results showed that the root-mean-square (rms) error could normally be minimized by using an averaging period of 5–10 minutes but to reduce the frequency of errors in excess of a 10-knot or higher threshold a shorter averaging period was better; in general the shorter the lag and the higher the threshold, the shorter the averaging

period necessary to minimize the frequency of errors exceeding that threshold. The results suggested that the original provisional recommendation of the International Civil Aviation Organization (ICAO) (1967) for the use of a 2-minute average, a recommendation which they recently confirmed (ICAO, 1974), appeared to be a satisfactory compromise, at least for summer and winter in southern England.

In the study of winter turbulent cases the question was posed whether the results for *orthogonal components* of the vector errors, across and along the runway direction, for example, would be different; some evidence was presented to suggest tentatively that the optimum averaging period for reducing the frequency of error components in excess of 10 knots may be significantly shorter for the across-runway component. Errors in the longitudinal component are usually more critical since these can result in significant vertical deviations from the intended glide-slope on approach, causing a 'short' heavy landing, a 'long' landing or an overshoot. This report presents the results of a re-analysis of the combined wind data for summer 1973 and winter 1973–74, the longitudinal and lateral components of the vector error being considered separately.

The data

The basic data comprised series of 30-second wind averages recorded by the Meteorological Office Mk 5 wind system at Heathrow during the periods 3 May–7 August 1973 and 20 December 1973–25 March 1974. The methods of selection of suitable 'turbulent' periods for analysis were broadly similar for winter and summer samples (for example, mean wind speed 15 knots or more, cumulonimbus cloud present, passage of fronts/squalls); for details the reader is referred to Hardy (1974) and Dutton (1975).

The final summer sample totalled 79 hours (32 periods) and the winter sample 287 hours (47 periods).

Detailed information on runway usage during the selected periods was obviously necessary since wind components along and across the direction of the runway in use were required for this analysis; this information was obtained from Air Traffic Control arrival/departure records held by the Civil Aviation Authority.

Analysis

The object of the investigation was to compare, on a large number of occasions, the wind which might be supplied to the pilot with the wind which he would actually have encountered some minutes later at touchdown or take-off. The departure or error is defined as the magnitude of the difference between the forecast wind component (along- or across-runway) and the actual or encountered component that affected the aircraft at or near touchdown or take-off. The forecast or reported wind was taken as the observed wind averaged over a period of time varying from 30 seconds to 10 minutes (simple arithmetic averaging of the east–west and north–south components of the 30-second winds being used) and the actual wind was taken as the 30-second wind average some time (lag) later; this lag, which represented the interval between the wind observation and the aircraft touchdown or take-off, was also varied from 30 seconds to 10 minutes.

For all the 79 sample periods totalling 366 hours the across-runway and along-runway error components at every time-step, for 20 averaging periods and 20 lags, were evaluated and various statistics of these errors were computed.

Results and discussion

(a) *Root-mean-square errors*

Figure 1(a–b) shows the variation of rms errors as a function of averaging period for various lags from 30 seconds to 10 minutes. Although the variation is very similar for each of the two components, the optimum averaging time from the point of view of minimizing the rms error is consistently slightly shorter for the across-runway component. For lags of 2 minutes or more a 5- to 10-minute average appears to be the optimum for the along-runway component, while a 4- to 8-minute average is better for the across-runway component.

(b) *Percentages of errors exceeding given thresholds*

Figures 2 and 3 show the variation with averaging period, for various lags, of percentages of errors (out of a total of 40 802) exceeding 10 knots and 14 knots respectively.

(i) *10-kn threshold* (*Figure 2*)

For lags of 2 minutes or more a shorter optimum averaging period is indicated for the across-runway component; at shorter lags a 1- to 2-minute average is best for both components.

(ii) *14-kn threshold* (*Figure 3*)

Here a short averaging period is favoured for most lags for both components but again there is a tendency for the optimum averaging period to be shorter for the across-runway component. In addition the frequency of errors exceeding this threshold is a more sensitive function of averaging period for the across-runway component. In general the frequencies for the latter component are about double those for the along-runway component.

(iii) *Higher thresholds*

The results for higher thresholds show that, for both components, the higher the threshold the shorter the averaging period necessary to reduce the number of errors exceeding the threshold.

Table I lists percentage frequencies of errors within the selected sample exceeding thresholds of 6, 10, 14 and 20 kn for lags and averaging periods of 2, 5 and 10 minutes. Table II contains estimates for summer, winter and combined summer/winter, of the *true overall* frequencies of errors in excess of 10 kn for a lag of 5 minutes. The figures in brackets are the reciprocals of the true frequencies (rounded to the nearest hundred) and represent the average number of take-offs/landings in which one error of 10 kn or more is encountered. The figures for 'magnitude of total vector' are taken from the original analyses by Hardy (1974) and Dutton (1975). The estimation of the true overall frequencies is based firstly on Hardy's partly subjective assessment that, for the summer investigation, the overall frequency of errors of 10 kn or more would be about one-tenth of the frequency within the selected 79-hour sample, and secondly on the assumption that, for the winter cases, all errors of 10 kn or more within the quality-controlled recorded data (1775 hours) were included in the 287-hour sample, and that the 1775 hours of data could be considered unbiased from a meteorological point of view.

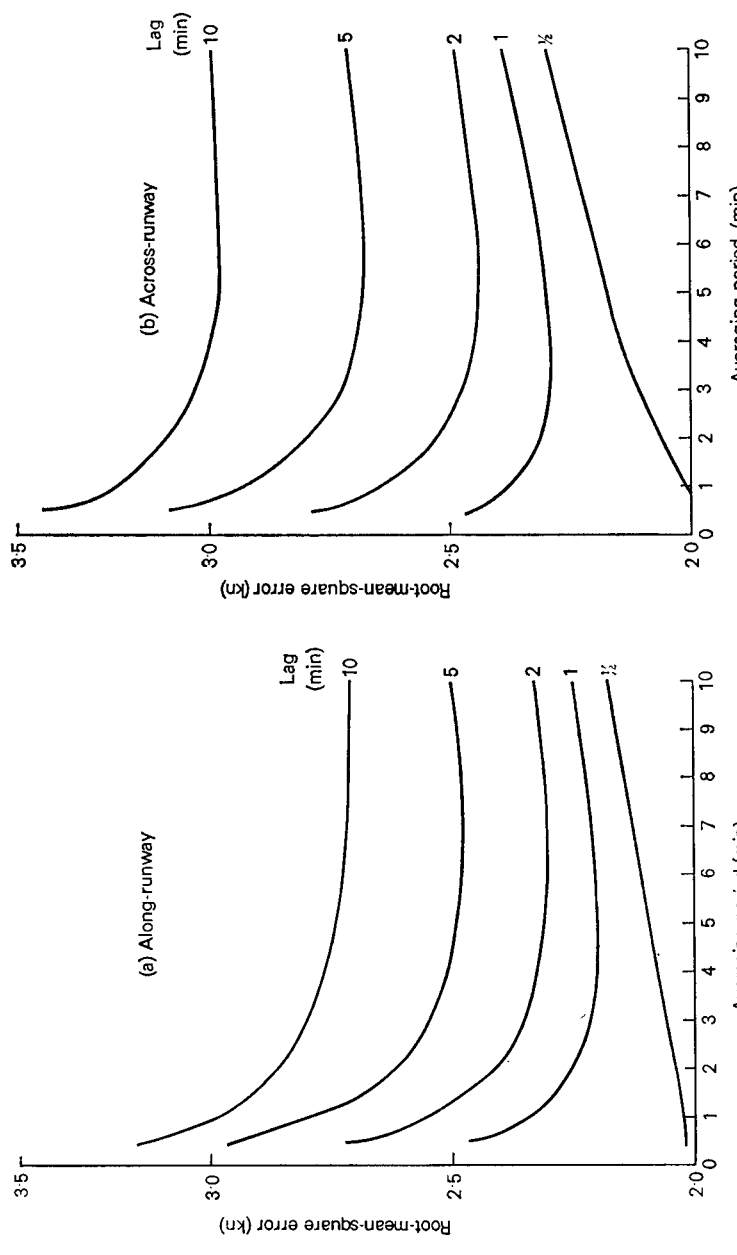

FIGURE 1—VARIATION OF ROOT-MEAN-SQUARE ERROR WITH LAG AND AVERAGING PERIOD (HEATHROW, SUMMER 1973 + WINTER 1973–74)

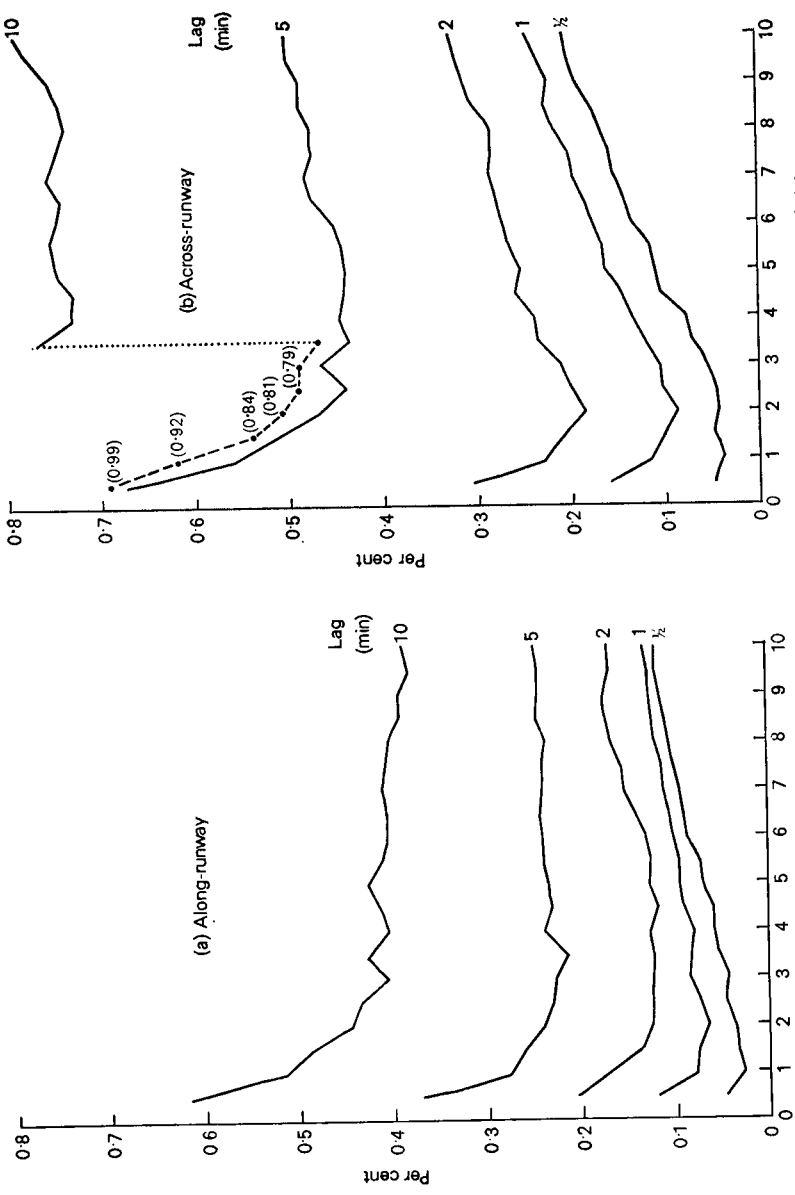

FIGURE 2—PERCENTAGE OF ERRORS ⩾ 10 KNOTS—VARIATION WITH LAG AND AVERAGING PERIOD (HEATHROW, SUMMER 1973 + WINTER 1973–74)

The left-hand part of the topmost across-runway trace has been displaced by 0.3 per cent; bracketed figures denote actual values.

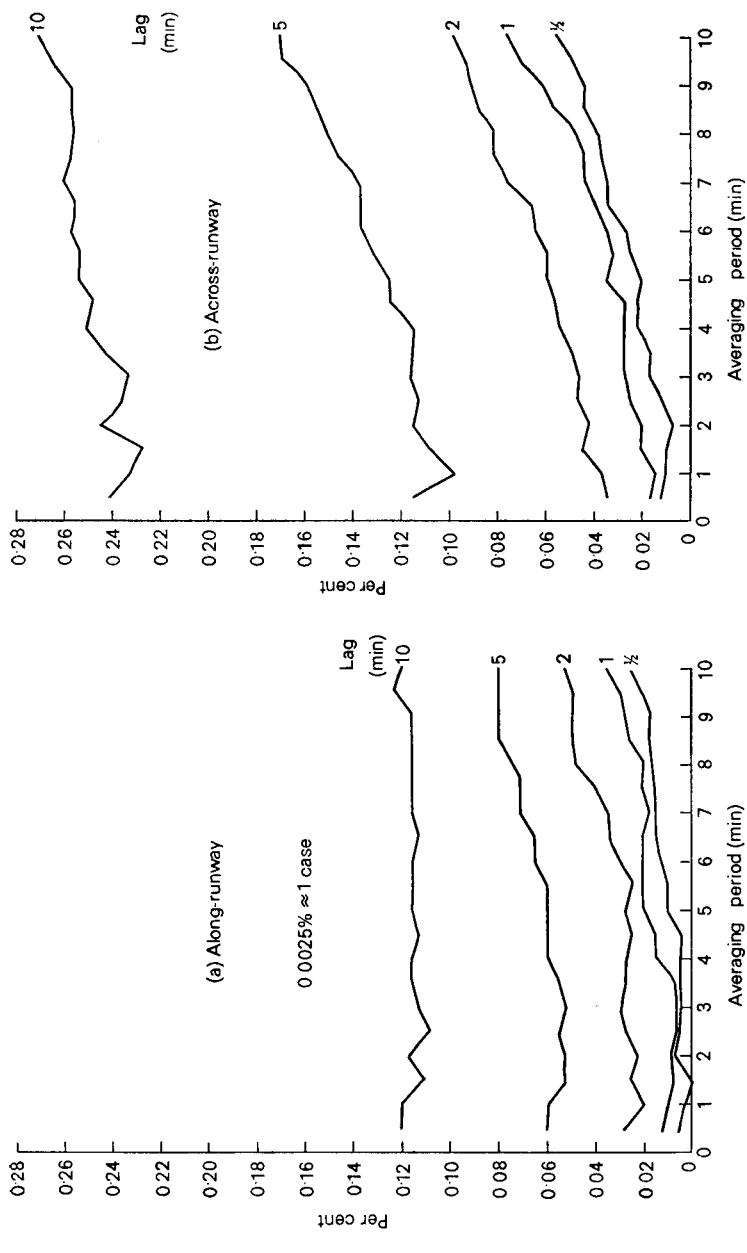

FIGURE 3—PERCENTAGE OF ERRORS ⩾ 14 KNOTS—VARIATION WITH LAG AND AVERAGING PERIOD (HEATHROW, SUMMER 1973 + WINTER 1973–74)

TABLE I—PERCENTAGE FREQUENCIES OF ERRORS EXCEEDING VARIOUS THRESHOLDS (SUMMER + WINTER)

Averaging period *min*	Lag *min*	Along-runway component Threshold (kn) 6	10	14	20	Across-runway component Threshold (kn) 6	10	14	20
	2	2·25	0·128	0·022	0·0	2·63	0·184	0·042	0·007
2	5	2·92	0·240	0·052	0·003	3·73	0·468	0·115	0·032
	10	4·19	0·444	0·118	0·017	5·22	0·811	0·245	0·071
	2	1·71	0·128	0·027	0·0	2·16	0·253	0·059	0·017
5	5	2·37	0·233	0·059	0·005	3·00	0·441	0·125	0·044
	10	3·59	0·424	0·115	0·025	4·42	0·745	0·253	0·081
	2	1·76	0·169	0·052	0·005	2·31	0·324	0·098	0·020
10	5	2·37	0·248	0·079	0·015	2·95	0·502	0·169	0·049
	10	3·37	0·387	0·120	0·027	4·38	0·787	0·270	0·098

(1 case ≈ 0·0025 per cent)

TABLE II—ESTIMATED TRUE PERCENTAGE FREQUENCIES OF ERRORS ⩾ 10 KNOTS FOR A LAG OF 5 MINUTES

	Averaging period *min*	Winter	Summer	Combined
	2	0·0291	0·0439	0·0365
		(3400)	(2300)	(2700)
Along-runway component	5	0·0230	0·0561	0·0395
		(4300)	(1800)	(2500)
	10	0·0239	0·0610	0·0424
		(4200)	(1600)	(2400)
	2	0·0572	0·0842	0·0707
		(1700)	(1200)	(1400)
Across-runway component	5	0·0511	0·0866	0·0688
		(2000)	(1200)	(1500)
	10	0·0516	0·1159	0·0837
		(1900)	(900)	(1200)
	2	0·1230	0·1680	0·1455
		(800)	(600)	(700)
Magnitude of total vector	5	0·1070	0·1765	0·1417
		(900)	(600)	(700)
	10	0·1025	0·2090	0·1558
		(1000)	(500)	(600)

Figures in brackets are reciprocals of true frequencies (rounded to the nearest hundred) and represent the average number of take-offs/landings in which one error of 10 knots or more is encountered.

The 'combined' overall frequencies in Table II show that for the two seasons combined and with an averaging period of 2 minutes, errors in the more important along-runway component of 10 kn or more (about 1 in 2700) occur with about a half of the frequency of across-runway errors (about 1 in 1400) and about a quarter of the frequency of total vector errors (about 1 in 700) exceeding the same threshold. The differences in the statistics of large errors for the two components can be explained on the assumption that the large vector errors were frequently associated with appreciable (but less than 90-degree) wind-direction shifts. In turbulent wind conditions it is often the case that the aircraft lands or takes off roughly into the mean wind direction (with a headwind component); in this situation, if a sudden shift in wind direction occurs, the associated change in across-runway component will normally exceed the change in along-runway component.

Conclusion

The results of this study and others (Hardy, 1974 and Dutton, 1975) have shown that, for Heathrow (and similar terrain in southern England) the 2-minute averaging period, recommended by ICAO for this purpose, is particularly effective for reducing the frequency of errors exceeding a threshold of about 10 to 14 kn (10 kn for summer months, 14 kn for winter months), but that its use inevitably results in increased rms error and frequency of errors in the range 0–10 kn, which a 5- to 10-minute mean reduces more efficiently. The results have also illustrated well that, whatever the averaging period (within the ½- to 10-minute range), the use of as short a lag as possible is of paramount importance. During lengthy periods of strong winds when there are no large abrupt changes of mean wind speed and/or direction, conditions quite frequently experienced during the winter months, the use of a 5- to 10-minute average has proved markedly superior to that of a shorter-period average. On the other hand when there are frequent large variations in mean wind speed and/or direction such as those associated with the passage of major fronts (synoptic scale) or with convective activity including mesoscale squall lines, the use of a short averaging period of ½ minute to 3 minutes is favoured. These results apply both to along-runway and across-runway wind components and also to the vector-error magnitude.

In general it seems that the ICAO-recommended 2-minute average wind provides an adequate compromise, particularly when the lag between the supply of the wind report and its use is less than 5 minutes.

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551.508.952

INSTALLATION OF A DOBSON OZONE SPECTROPHOTOMETER IN THE SEYCHELLES

By J. H. CONVERY

Summary

A Dobson spectrophotometer was installed in November 1975 on the island of Mahé, Seychelles. The spectrophotometer is described and the pre-installation tests and operational routine are outlined.

Introduction

In the last five years there has been increased interest in the trend of total atmospheric ozone (O_3). This interest has largely arisen through fears that the amount of atmospheric ozone might be reduced by reactions involving exhaust products from the engines of supersonic transport aircraft (SST) and

chlorine produced by the action of solar ultraviolet on chlorofluoromethane (freon) compounds released from aerosol cans at the surface and diffusing upwards into the stratosphere. Discussion of these problems has been hampered by lack of information on the amount of ozone in the atmosphere and on the way in which it is changing. A recent statement by the World Meteorological Organization (1976) outlines the problems associated with the measurement of ozone and the interpretation of the results obtained.

Although satellite observations have greatly improved the spatial coverage of ozone measurements, they are limited to heights above 30 km and it is accepted that there is still a need for accurate values of total ozone measured from the ground. For 40 years the instrument for measuring total ozone, universally acknowledged as the standard by which all others are judged, has been the Dobson spectrophotometer. The geographical distribution of these instruments in equatorial regions at the beginning of 1975 is shown in Figure 1. Clearly, closure of the observing station at Gan early in 1976 has left a significant gap in the already thin equatorial coverage. As a means of filling this gap the Meteorological Office decided that, if possible, they should set up a new ozone observing station at Mahé, Seychelles. With the agreement of the Seychelles Directorate of Civil Aviation the station was opened at the new rawinsonde office at Mahé (4°40′ 36″S, 53°39′ 54″E) on 1 November 1975. As a further contribution to equatorial ozone measurement the Meteorological Office plans to open a second new observing station on the island of St Helena (15°56′ 18″S, 05°39′ 24″W) in October 1976.

Principles of operation of the Dobson spectrophotometer

The Dobson spectrophotometer is a double-beam monochromator operating in the ultraviolet Hartley absorption band of O_3 (290–340 nm).* It is shown schematically in Figure 2. Light from the sun or zenith sky enters through the window W and after deflexion passes through the narrow entrance slit S_1. From S_1 the light passes through a spectroscope (lens L_1, prism P_1 and mirror M_1) which forms a spectrum in the focal plane of the instrument where slits S_2 and S_3 are located. The position of the spectrum can be adjusted, by refraction through the quartz plate Q_1, so that light of the appropriate wavelength falls on slits S_2 and S_3.

The wavelengths chosen to pass through the slits S_2 and S_3, though separated by only about 20 nm, suffer strong differential absorption by the ozone in the atmospheric transmission path. The wavelengths used operationally are 305·5 nm with 325·4 nm, and 317·6 nm and 339·8 nm (described by Dobson as the *A* and *D* wavelength pairs respectively). The shorter, more strongly absorbed wavelength of each pair passes through S_2 and the longer, less strongly absorbed wavelengths through S_3. The instrument operates on the 'null' principle. The response of the detector to the light from S_2 and S_3 is balanced by attenuating the S_3 beam; the amount of attenuation required is measured and related to the total ozone in the optical path from the instrument to the top of the atmosphere. A sector disc SD, giving 78 alternations of light and dark per second, alternately passes light from S_2 and from S_3. After passage through a second matched spectroscope arrangement (L_2, P_2, M_2) and an interference filter, F, which serve to reduce unwanted background light, the radiation falls

* Historically the wavelengths have been designated in ångström units (1Å = 10^{-1} nm).

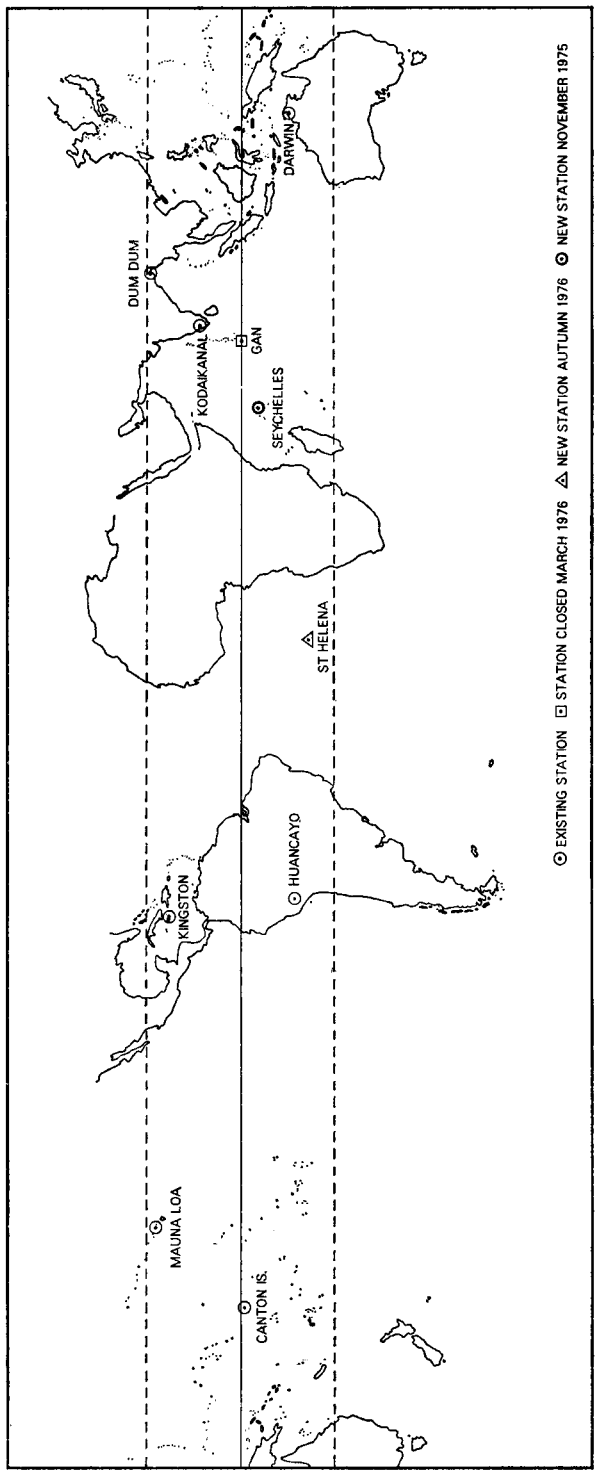

FIGURE 1—OZONE OBSERVING STATIONS (EQUATORIAL)

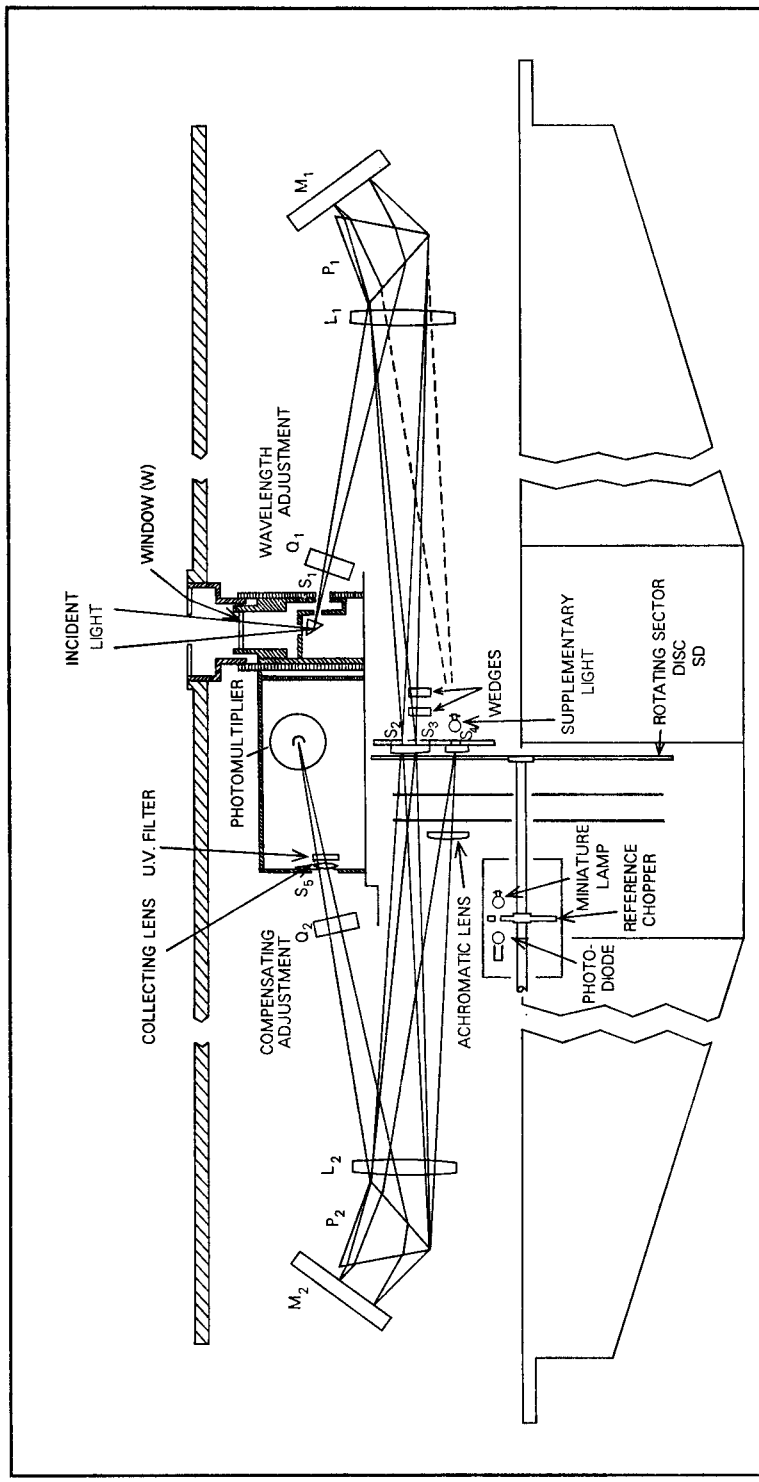

FIGURE 2—OPTICS OF THE DOBSON SPECTROPHOTOMETER
Based on Figure 3 in Dobson (1957). Slit S_4 is now only used for calibration purposes.

upon a photomultiplier cathode and any difference in response appears as an alternating voltage at the photomultiplier anode. This alternating signal is amplified and detected through a phase-sensitive detection system, the reference for which is derived from a small photodiode viewing a miniature light source through a slot in a rotating reference chopper mounted on the spindle of the sector disc SD. The signal appears ultimately as a current shown as an offset on a zero-centred microammeter. A full description of the electronics of the instrument has been given by Else *et alii* (1969).

The differential attenuation is measured by introducing into the optical path in front of S_3 an optical element (R) consisting of two pairs of quartz plates, each pair sandwiching a layer of a metallic deposit known as chromel. The sandwiches are graded in opposite directions and when introduced into the beam give a variation in transmission characteristic that is roughly wedge-shaped and the optical element is therefore referred to as an 'optical wedge'. The position of the wedge, and hence the degree of attenuation, is indicated by a graduated dial on the spectrophotometer casing; it is adjusted until the output current offset is reduced to zero. Clearly the dial reading at this wedge position is related to the total ozone measurement required. The spectrophotometer is described in detail by Dobson (1957).

The calibration of a Dobson spectrophotometer

The manufacturers of the Dobson spectrophotometer have found it impossible to produce wedges with identical optical characteristics, thus each instrument requires individual calibration. The relative opacity or gradient along the length of the wedge and an absolute value at some point on the wedge are required. In theory the determination of an absolute scale for the Dobson instrument should be possible at the observing station. If a series of observations are made on the sun as it rises to its zenith and if it is assumed that the total ozone has not changed during the observing period, then an absolute value for a point on the wedge can be deduced. In practice it has proved extremely difficult to obtain the very clear atmosphere required for such a calibration. The method used for absolute calibration is that one instrument, calibrated by observation on the sun at a high-altitude station in very clear air, is nominated as the international standard instrument. Substandard instruments are calibrated by a side-by-side comparison with the standard instrument through a range of sun heights. A very clear atmosphere is not essential for a side-by-side comparison, it being assumed that both instruments will suffer the same degree of interference from haze and dust. After an absolute comparison has been made, the drift in calibration of the wedge is monitored by the use of a standard lamp which produces a constant intensity of light.

The gradient of opacity of the wedge is determined by the use of a supplementary light source and a twin-lamp apparatus. The apparatus consists of a pair of balanced quartz–iodine lamps set above a split lens which can be located over the entrance window of the spectrophotometer. The supplementary light source is placed in front of S_4 (see Figure 2). S_2 is blanked off and light from the twin lamps, passing through the wedge and S_3, is balanced by adjustment of the wedge against the supplementary light. With the S_4 lamp at the same current, the twin lamps are then run individually and the new balance position of the wedge determined. The difference in the wedge positions for

the single and double lamps is a measure of the opacity which balances a doubling of lamp intensity. By adjusting the S_4 lamp intensity by small amounts and repeating the operation along the length of the wedge, a picture of the opacity of the wedge is built up.

The slit positions and optical alignment of the instrument are checked by using a mercury lamp and tuning on to particular spectral lines with Q_1 and Q_2.

The Seychelles spectrophotometer

Dobson Spectrophotometer No. 57 was manufactured in 1963 and after calibration by comparison with Dobson No. 1 at Oxford it was sent to the Commonwealth Scientific and Industrial Research Organization (CSIRO) at Canberra on an extended loan. From 1964 to 1973 it operated at Woomera and Perth, and on return to the United Kingdom was compared with the UK substandard, No. 41, at Bracknell. In the Antarctic summer of 1974–75 No. 57 was lent to the British Antarctic Survey to act as a travelling substandard. It visited the UK bases at Halley Bay, Argentine Islands and South Georgia.

On return to the United Kingdom it was decided to give No. 57 a thorough overhaul and to modernize the electronics. The RCA 1P28 photomultiplier was replaced by an EMI 9781A with a consequent increase in sensitivity by a factor of over 200. A transistorized system of amplification (Else *et alii*, 1969) replaced the original circuits designed 40 years ago. The modernization produced only a marginal improvement in the signal to noise ratio but electronics faults can now be rectified more simply by the replacement of a printed-circuit board.

Calibration of the Seychelles spectrophotometer

Before the instrument left Bracknell the Q-lever positions were calibrated by using spectral lamps. The lamps provide six wavelengths over the 34·3-nm range in which the Dobson is operated and the operational wavelengths can be set to within 0·05 nm. The gradient of the wedge was calibrated over 260° of dial at 2° intervals. The absolute calibration was determined by comparing Dobson No. 57 with No. 41, the UK substandard instrument. Dobson No. 41 was itself compared with the accepted World Meteorological Organization standard instrument, from Boulder, Colorado, at Belsk, Poland, in June 1974 (Losiowa, 1975).

Dobson No. 57 was air-freighted to the Seychelles in a custom-built box. Upon arrival the instrument was given three days to acclimatize while the facilities and calibration equipment were inspected. Mercury-lamp and standard-lamp tests were then carried out. Table I shows the Q_1 setting correction (ΔQ). ΔQ is the difference between the angular position of Q_1 determined by the mercury-lamp test on site (mean Q_1) and the angular position of Q_1 defined by the original mercury-lamp test at Bracknell (calibrated Q_1). The corrections

TABLE I—MERCURY-LAMP TESTS ON DOBSON NO. 57

Location	Date	Instrument temp.	Calibrated Q_1 setting	Mean Q_1	ΔQ
Bracknell	16.10.75	15·9°C	84·29	84·39	+0·10
Mahé	29.10.75	29·0°C	85·63	85·45	—0·18
Mahé	3.11.75	30·0°C	85·74	85·64	—0·10
Mahé	7.11.75	29·1°C	85·64	85·50	—0·14

ΔQ is measured in angular degrees.

found were within the limits of experimental error. The standard-lamp tests showed a change between the values obtained in the Seychelles and the pre-dispatch tests carried out at Bracknell. This change indicated that during transit there had been a small shift in the position of the optical wedge on its carriage. The relationship between the dial value and total ozone is complicated (Dobson, 1957) and will not be discussed in this paper. The change in standard-lamp values corresponded with a −0·6 per cent change in total ozone. A +0·6 per cent correction will be applied to all data from this instrument to accommodate this shift. The gradient of the wedge was checked by repeating the twin-lamp tests undertaken at Bracknell. The gradient observed was identical to that observed at Bracknell.

Routine observations in the Seychelles

The spectrophotometer is housed in a room attached to the balloon shed on the rawinsonde site which is situated on the north side of South Island. The main runway of the new airport now joins South Island to Mahé, the largest island in the Seychelles. The area round the site is dusty owing to the immediate proximity of two quarries and the airport perimeter road, which has a top surface of crushed coral. The ozone observations will be made at about 0830 local time, and it is hoped that this will be before quarry blasting has begun.

The ozone observations are made on a flat concrete circle situated some 20 metres clear of the building. Observations are made daily on the *A* and *D* wavelengths. It is hoped that the majority of observations will be made on the direct sun. Observations can be made on the zenith sky, clear or cloudy, but Thomas *et alii* (1974) estimate an increase in scatter of 2·7 per cent compared with direct-sun observations.

Once a month a mercury-lamp test and a standard-lamp test are carried out and the resulting data together with the daily observations are sent to Bracknell for computation. From Bracknell the computed daily ozone values are sent to the World Ozone Data Centre at Toronto in Canada.

Daily observations began at the Seychelles station on 1 November 1975. The quality of a Dobson observation depends very much on the care exercised in making the observation and the condition of the spectrophotometer, but with trained observers and a well-calibrated instrument, an error of less than ±2 per cent in total ozone should be possible. A four-month overlap of observations was achieved between the opening of the Seychelles station and the closure of the one on Gan on 1 March 1976. The total ozone values for the two stations are illustrated in Figure 3. The total ozone amounts are shown in Dobson Units (milli-atmo-centimetres).

Acknowledgements

I would like to thank Mr M. J. Longworth and Mr C. Brookes for their invaluable assistance in setting up Dobson No. 57 in the Seychelles. I would also like to thank Dr R. E. W. Pettifer for his guidance and advice.

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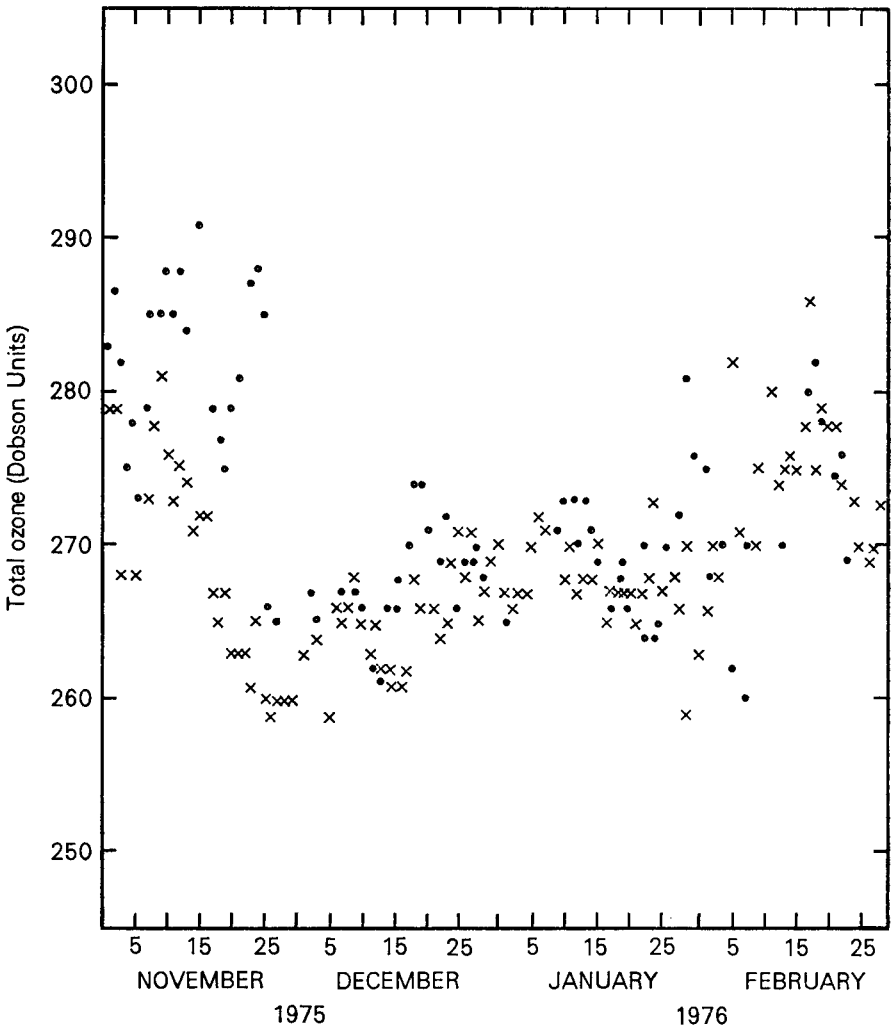

FIGURE 3—DAILY TOTAL OZONE AMOUNTS RECORDED AT GAN AND SEYCHELLES DURING A FOUR-MONTH OVERLAP PERIOD

x Gan ● Seychelles

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REVIEWS

Cloud physics and weather modification, by Yu. S. Sedunov. 240 mm × 170 m, pp. iv + 106, *illus.* (translated from the Russian by Israel Program for Scientific Translations, Jerusalem), John Wiley and Sons Ltd, Baffins Lane, Chichester, Sussex, 1974. Price: £6·75.

This book is a translation of a collection of five papers published in 1970 in the USSR. The first of these is a report by the editor of the weather-modification program in the USA. It represents the findings of a Soviet delegation who visited several American university and government agencies engaged in cloud-physics and weather-modification research during the autumn of 1969. The report is mainly factual, although there are some generalized value judgements. No comparisons with similar research efforts in the USSR are offered. The article is interesting in providing a limited Soviet view of some United States research in the late sixties but it is likely to be of greater value to the historian than the scientist today.

The second article is entitled 'Modifications of clouds and precipitation in central European USSR' and is written by I. V. Litvinov. The title is rather ambiguous as the author attempts to predict an upper limit to precipitation amounts which might be obtained by cloud seeding in a particular region of the Soviet Union. There is no discussion of the physics of the seeding process and the assumptions made are so gross and arbitrary that it is difficult to see any value in the paper.

The third contribution, by E. L. Aleksandrov, is a survey of methods of measuring concentrations of cloud-condensation nuclei in the 'Aitken' region. The author categorizes instruments by the methods used to generate a super-saturation. There are sections on expansion chambers and also on thermal and chemical diffusion chambers.

The fourth paper is a review of the micro-physics of droplet coagulation by V. M. Voloshchuk. The concept of collision efficiency is developed in the contexts of droplet growth through coalescence and of the washout of small aerosol particles by cloud droplets. The approach is primarily theoretical.

The final article is by S. P. Belyaev. He extols the use of flash illumination and photography in aerosol research. In particular he considers the usefulness of the technique in the investigation of deposition and bouncing of particles on solid objects and into aspirated pipes, and in the study of concentration fluctuations and of droplet coalescence.

Apart from the fact that all of these papers are very dated, their choice for translation and publication in book form, under the title of 'Cloud physics and weather modification' is particularly inappropriate. Whatever scientific merit the two weather-modification papers may have had, it can only have been realized in front of a Soviet audience. This also applies to the third paper because the major advances in the field, at least up to the time of this report, have been made outside the USSR and are already well documented in the English literature. Neither of the remaining papers can be said to be a key contribution even in its own specialized area within cloud physics. This is all particularly disappointing, when, as at present, a detailed account of the physical principles and methodology underlying the claimed success of Soviet cloud and weather modification is so urgently required.

P. RYDER

Climate and the environment—the atmospheric impact of man, by John F. Griffiths. 215 mm × 135 mm, pp. 148, *illus.*, Paul Elek Ltd, 54–58 Caledonian Road, London N2 9RN, 1976. Price: £2·95.

This book is one of the first three publications in a new Environmental Studies series, and seems to be aimed at the pre-university or undergraduate non-scientist. Since so many books have appeared in recent years covering the general descriptive aspects of climatology (with or without applications), a newcomer to the lists would need to achieve considerable originality of approach and presentation in order to stand out. As indicated by the sub-title, the book's main theme is the consideration of man's reaction to his climatic conditions, and this is an estimable peg on which to hang a description of climate. However, parts of the book show signs of having been compiled much too hastily and explanations of meteorological phenomena are often oversimplified and do not follow logically from the evidence presented.

The first half of the book, devoted to the description of the basic climatic factors, is the more unsatisfactory in this respect. Most of the diagrams are taken from published sources and effort has not been made in all cases to ensure consistency between diagram, legend and text. Some diagrams contribute little to the general theme and appear to have been included as 'makeweights'. The largest chapter in the first half deals well with 'Radiation and the Energy Budget', but the details presented here (including the astronomical and heat-budget equations) do not match the simple descriptive tone of the other chapters. The chapter entitled 'Climatic Patterns' is a curious collection of material on typical seasonal temperature variations, definitions of humidity measures, an introduction to climatic classification, a discussion of temperature fluctuations on time-scales of seconds and 10^5 years and, finally, a presentation of the world's maximum rainfalls versus duration (with, incidentally, the enveloping curve's equation in different units on the diagram and in the text).

The second half of the book is concerned with applications of climatology, and here again there is inconsistency of presentation between the section on Human Biometeorology, which gives lots of rather complex equations and diagrams, and the other chapters where simple descriptions suffice. The 'Climate and Building' chapter is a good straightforward analysis of the importance of a knowledge of climate to those involved in the planning and designing of habitable structures. Those who have experienced the rigours of working in offices not capable of withstanding the vagaries of the local climate may derive a certain grim amusement from the following quotation in the section on primitive architecture:

> 'The worst the modern architect faces is a dissatisfied client; when the primitive architect errs, he faces a harsh and unforgiving Nature.'

The remaining chapters on agriculture, atmospheric modification, city climates and miscellaneous applications of climatology are well constructed and readable. The second half of the book can thus be recommended as a non-technical description of some of the applications of climatology which are important to man's well-being, but the basic climatological ground-work in the first half of the book is not well planned or executed.

J. S. HOPKINS

NOTES AND NEWS

Post Office 'Viewdata service'

The Meteorological Office has agreed to take part in a trial of the Post Office's 'Viewdata service'. 'Viewdata' uses existing telephone lines to connect a Post Office data bank with the subscriber's television set and makes it possible for information to be called up on demand. The adaptation of the television set is similar to that needed for reception of the experimental BBC 'Ceefax' and IBA 'Oracle' transmissions. As at present envisaged, 'Viewdata' may prove to be a means of providing specialized meteorological services for groups such as climbers and walkers, yachtsmen, farmers and others which will cover all costs.

Symbol for specification of temperature difference or interval

Until about 1961 the elevated degree symbol ° was used indifferently to indicate both spot values and ranges, differences, depressions, increases, decreases, errors, tolerances etc. of temperatures on the Centigrade and Fahrenheit scales. In 1962 the Comité International des Poids et Mesures (CIPM) approved the use of the degree Kelvin with symbol °K to indicate the unit both for a difference between two thermodynamic temperatures and for a thermodynamic temperature itself. This decision rendered the form °A obsolete. The CIPM decided at the same time, that, if judged necessary, the international symbol 'deg' could be be used for the indication of an interval or difference of temperature. Since the Fahrenheit scale was not then totally obsolete the *Meteorological Magazine* started to use the form 'degC' to indicate temperature intervals on what is now properly called the Celsius scale. At its 13th meeting in 1967 the Conférence Générale des Poids et Mesures (CGPM) decided that the unit of thermodynamic temperature should be denoted by the name 'kelvin' and that its symbol should be 'K'. The CGPM also stated that temperature intervals might also be expressed in degrees Celsius, and that the decisions taken by the CIPM in 1962, including the use of 'deg' were abrogated but that usages which derived from these decisions remained permissible for the time being. British Standard BS5555: 1976* recommends 'K' to denote a temperature interval but also permits the use of '°C'. In conformity with this recommendation the *Meteorological Magazine* will in future normally use 'K' to denote a temperature interval unless special circumstances require the use of '°C', and the obsolescent form 'deg' will be discontinued. It should be noted that the unit 'kelvin' in common with other units named after individuals such as 'henry', 'newton', 'pascal' and 'watt' is not spelt with an initial capital letter, despite the use of a capital for the symbol 'K'.

*London, British Standards Institution, 1976: SI units and recommendations for the use of their multiples and of certain other units. BS5555:1976.

OBITUARIES

It is with regret that we have to record the death on 21 July 1976 of Mr H. W. Jones, Assistant Scientific Officer, of Manchester Airport, and on 23 July 1976 of Mr T. Ross, Second Engineer, Ocean Weather Ship Base, Greenock.

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RAINDROP-SIZE DISTRIBUTIONS IN A HILLY REGION

By C. A. NICHOLASS and P. R. LARKE

SUMMARY

Raindrop-size distributions have been measured in a hilly region of North Wales for the summers of 1972–74 and used to calculate empirical relationships between certain parameters important in radar and radio meteorology.

The observed rainfall rates were between 0·1 mm h^{-1} and 47·9 mm h^{-1}, and about 34 000 raindrop-size distributions were used to calculate various relationships by a linear regression technique.

The drop-size distributions at the lower rainfall rates showed close agreement with the Marshall–Palmer exponential distribution, but for higher rates there was an increasingly noticeable deficiency of both very small and very large drops.

The radar reflectivity factor (Z) and rate of rainfall (R) were calculated from each distribution, and the empirical relationship of the form $Z = AR^B$, where A and B are 'constants'. The constants calculated were higher than those measured by most other authors who used a similar regression technique. A comparison of areal radar measurements using the widely accepted value for the exponent (constant B) of 1·6 and the value of 1·8 derived from distrometer data from North Wales produced an improvement in the accuracy of measurements of about 10 per cent for rainfall rates less than 1 mm h^{-1}, and 2–3 per cent for rainfall rates equal to or greater than 1 mm h^{-1}.

The Z–R relationships have been calculated for various synoptic types and storm by storm. These results show wide variability and it is concluded that radar systems should be calibrated using a few telemetering gauges in the area of interest.

Empirical relationships between rate of rainfall, attenuation, median drop-size diameter and liquid water content have also been derived, and these confirm the results of other authors.

INTRODUCTION

Size distributions of raindrops have been measured and interpreted in many parts of the world, largely because they are important in determining the accuracy of measurements of precipitation using radar and assessing the problem of attenuation in radio communication caused by hydrometeors.

It has been shown that the drop-size distributions are highly variable in space and time, and because of this the empirical relationships between the various parameters that can be derived from them (such as radar reflectivity factor, rate of rainfall and liquid water content) are subject to wide variations. (For a survey of these relationships see for example Stout and Mueller (1968).)

As a part of the Dee Weather Radar Project (Harrold *et alii* (1974)), raindrop spectra have been measured at two sites in North Wales to investigate their variability in a hilly region where accurate measurements of areal precipitation are difficult to achieve. Harrold *et alii* showed that although radar measurements of precipitation could be made with sufficient accuracy for many hydrological purposes, one of the major limitations to the accuracy obtainable was the change in the drop-size distribution over the area of measurement. The purpose of this paper is to describe the results derived from the very large number of drop-size spectra measured, to show the difficulties in achieving accurate rainfall measurements from a radar system, and to calculate the attenuation of microwave radiation caused by rainfall.

Instrumentation

The raindrop spectra were measured using a Joss distrometer* (Joss and Waldvogel (1967)). This instrument has a collecting area of 50 cm^2 and a crystal clock provides time pulses at one-minute intervals. The mechanical momentum of each raindrop is transformed into an electric pulse, and thereby the size of each drop is measured using a pulse-height analyser. Each drop is classified into one of 20 size categories ranging from 0·3 mm to 6·0 mm in diameter. However, it was found that in the first eight size intervals the numbers of drops measured alternated between many and a few for consecutive sizes, a defect attributed to slight inaccuracy in calibration. This was overcome by pairing size intervals, therefore reducing the first eight to four larger size ranges.

The two sites chosen were at Carrog and Bala (see Figure 1). The instrument was at Carrog during the summers of 1972 and 1974, and at Bala in the summer of 1973. The distrometer was mounted with its rim flush with the surrounding ground and close to a Plessey MM37 tipping-bucket rain-gauge which served as a check by providing an independent measure of rainfall. A comparison of gauge- and distrometer-measured rainfall is shown in Figure 2; the annual totals for the coincident periods are shown in Table I.

TABLE I—RAINFALL MEASURED BY GAUGE AND DISTROMETER

Year	Gauge-measured rainfall *mm*	Distrometer-measured rainfall *mm*	Hours of data
1972	104·0	119·1	1580
1973	145·6	154·6	2256
1974	93·6	82·2	1275

Aniol (1974) indicated that a distrometer underestimates the rainfall in strong winds, an occurrence which would be expected in North Wales. Table I does not substantiate this but both Figure 2 and Table I demonstrate that, though errors are likely both with gauge and distrometer, the measurements are sufficiently alike for us to assume that the distrometer correctly measures raindrop distributions.

* Dr Joss informs us that the word *distrometer* is derived from *distr*ibution *meter* and is the correct spelling for the instrument developed by him and Dr Waldvogel. The spelling *disdrometer* had previously been used for another instrument (Editor).

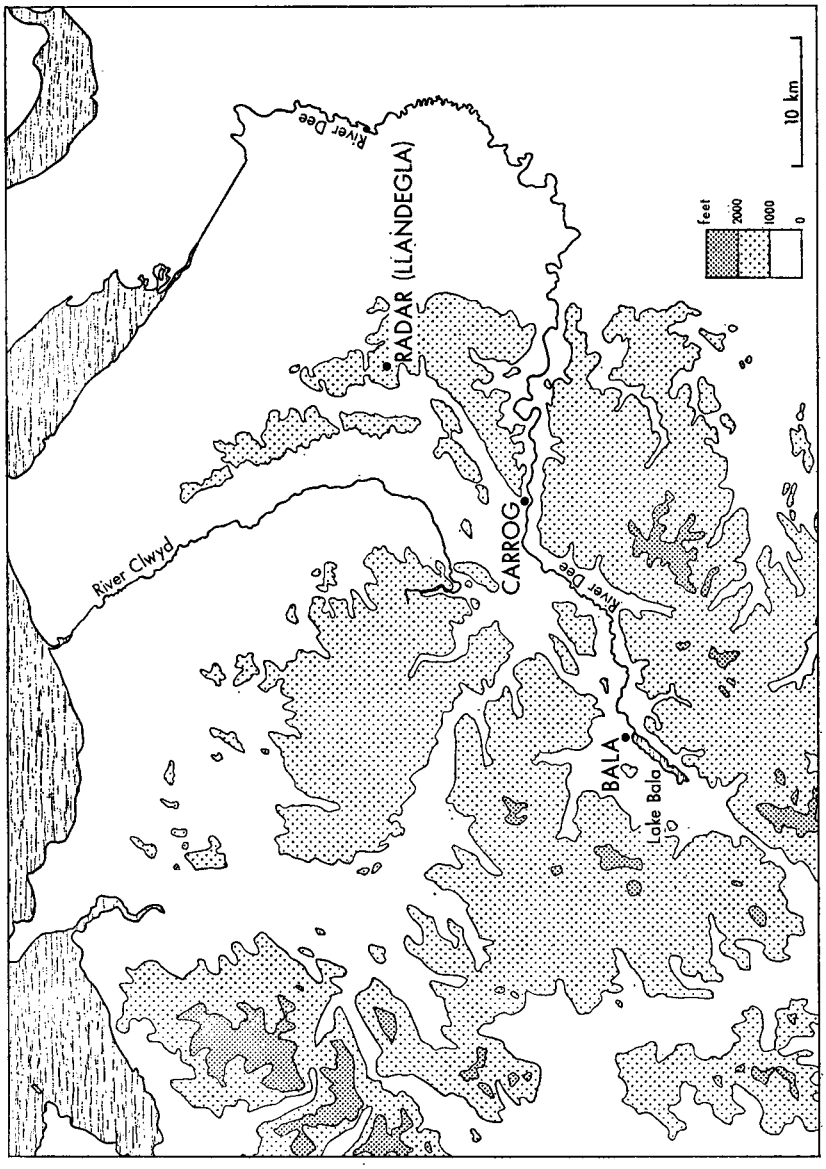

FIGURE 1—A MAP OF NORTH WALES SHOWING THE LOCATIONS OF THE DISTROMETER SITES AT BALA AND CARROG

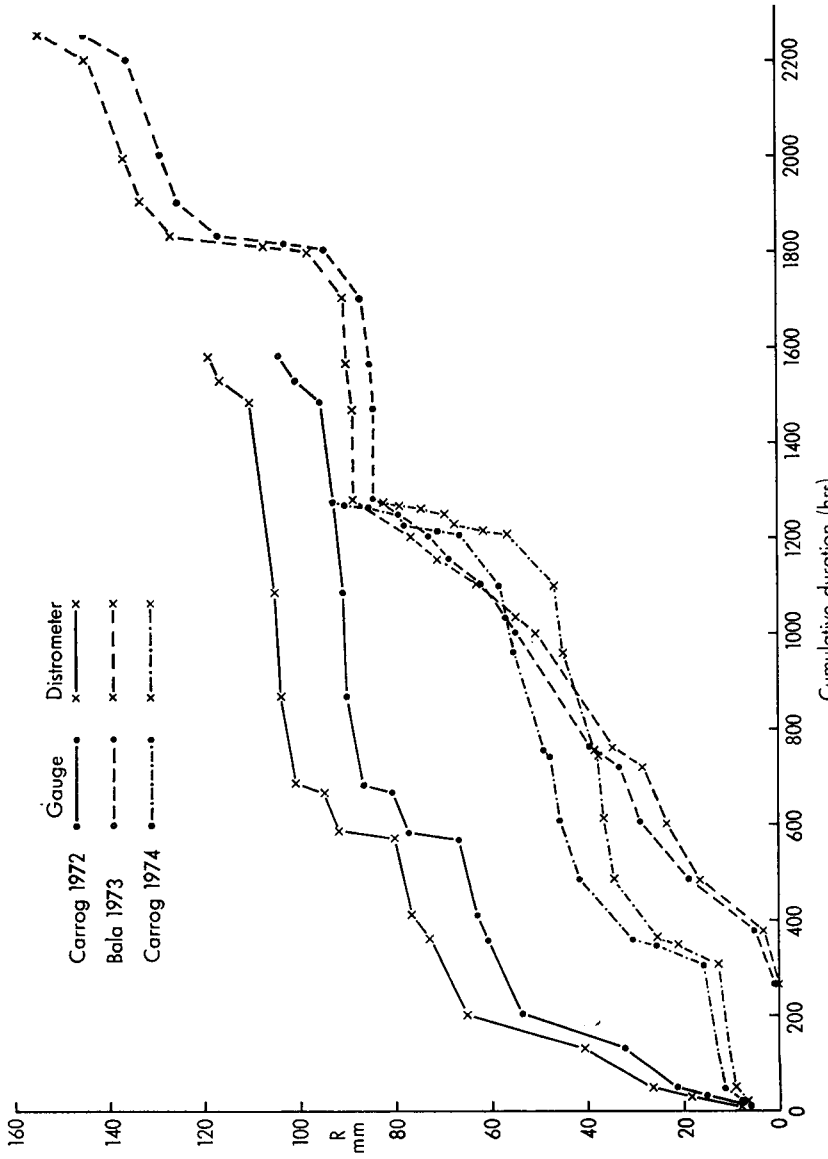

FIGURE 2—CUMULATIVE RAINFALL MEASURED BY GAUGE AND DISTROMETER

Drop-size distributions

The drop-size distribution can be defined by the summation over all sizes of the number of drops in a unit volume (N_D) with diameters in the range D to $D+\Delta D$.

Although the distrometer measures the number of drops (N) of given sizes hitting a sensor of area 50 cm^2 per minute (i.e. a flux) it is normal to express the drop-size distribution in terms of N_D which is the number of drops per unit volume per unit size interval with a diameter D. The size intervals used and their respective raindrop terminal velocities are shown in Table II.

TABLE II—TERMINAL VELOCITY OF RAINDROPS

Category	Minimum diameter *mm*	Maximum diameter *mm*	Terminal speed $m\ s^{-1}$
1	0·3	0·5	1·62
2	0·5	0·7	2·47
3	0·7	1·0	3·36
4	1·0	1·4	4·61
5	1·4	1·6	5·41
6	1·6	1·8	5·87
7	1·8	2·1	6·40
8	2·1	2·4	6·98
9	2·4	2·7	7·48
10	2·7	3·0	7·88
11	3·0	3·3	8·21
12	3·3	3·7	8·50
13	3·7	4·1	8·77
14	4·1	4·5	8·95
15	4·5	5·0	9·05
16	5·0	6·0	9·12

Marshall and Palmer (1948) related their drop-size distributions measured in Canada by $N_D=N_0e^{-\lambda D}$ where N_0 is the value of N_D for $D=0$ and λ is a function of the rate of rainfall, $\lambda=41R^{-0\cdot21}$ cm^{-1}. The results obtained in North Wales are compared with this widely accepted distribution.

The calculated parameters have been compared using the empirical relationship in the form of the afore-mentioned Z–R relationship i.e. $Z=AR^B$ where A and B are 'constants'.

Stout and Mueller (1968), in their review, have shown that these 'constants' have in fact widely varying values dependent on location, synoptic weather type and probably the method of measurement.

The mean raindrop-size distributions for a number of selected rates of rainfall have been computed for each of the three summers, by averaging the drop spectra for all minutes when the rainfall rate was within specific bounds. For example, all minutes with rainfall rates between 0·6 and 1·5 mm h^{-1} have been averaged to give the mean distribution for about 1 mm h^{-1} (0·95 mm h^{-1} in fact). If only minutes with exactly 1 mm h^{-1} had been chosen, the data sample would have been rather small. The mean distributions for three fixed rates of rainfall are shown in Figure 3. For comparison the Marshall–Palmer (1948) distributions for the equivalent rainfall rates are also included.

It can be seen that the mean distributions for each year were very similar to one another and to the appropriate Marshall–Palmer distribution. However, there was a tendency for fewer small and fewer very large drops to be measured than would have been expected from the Marshall–Palmer distribution. These

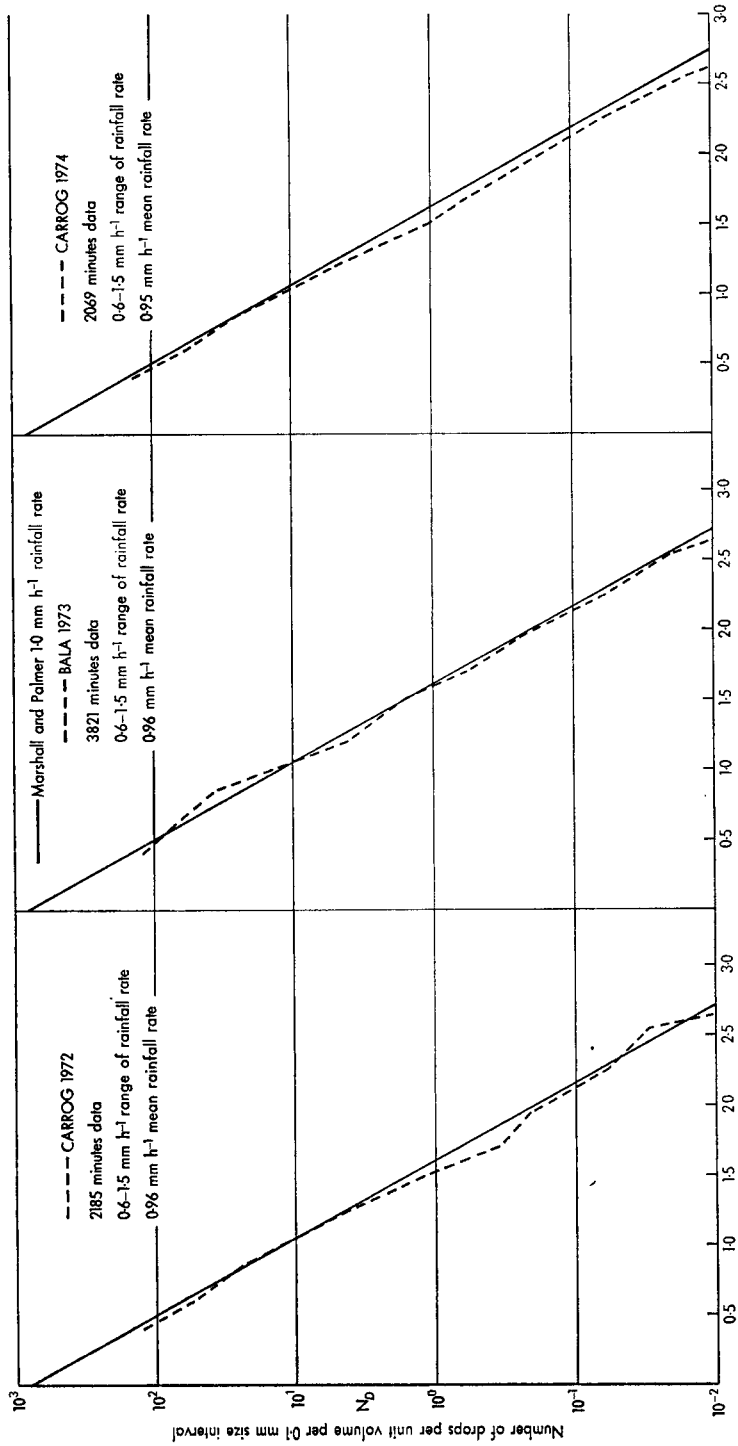

FIGURE 3—THE MEAN DROP SIZE DISTRIBUTIONS FOR THREE SELECTED RATES OF RAINFALL

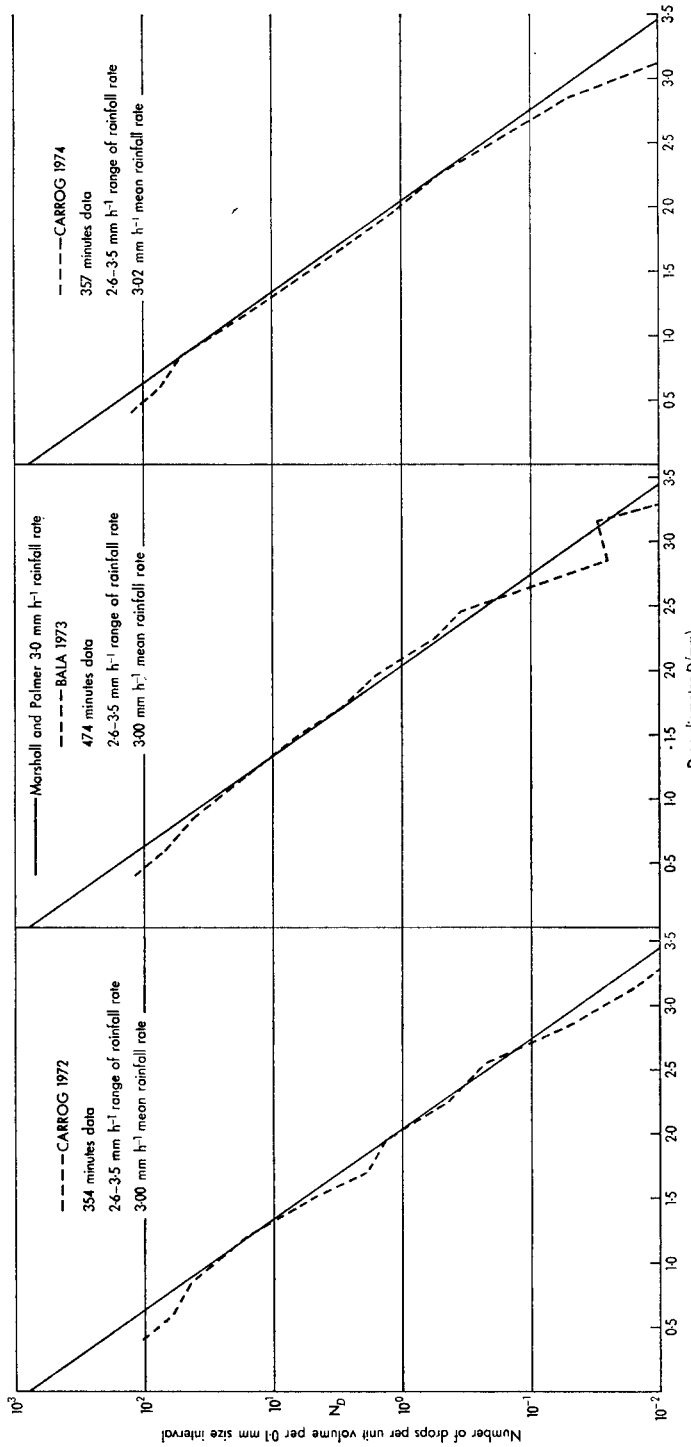

FIGURE 3—*continued*

Carrog 1972 mean rainfall rate should read 2.98 mm h^{-1}

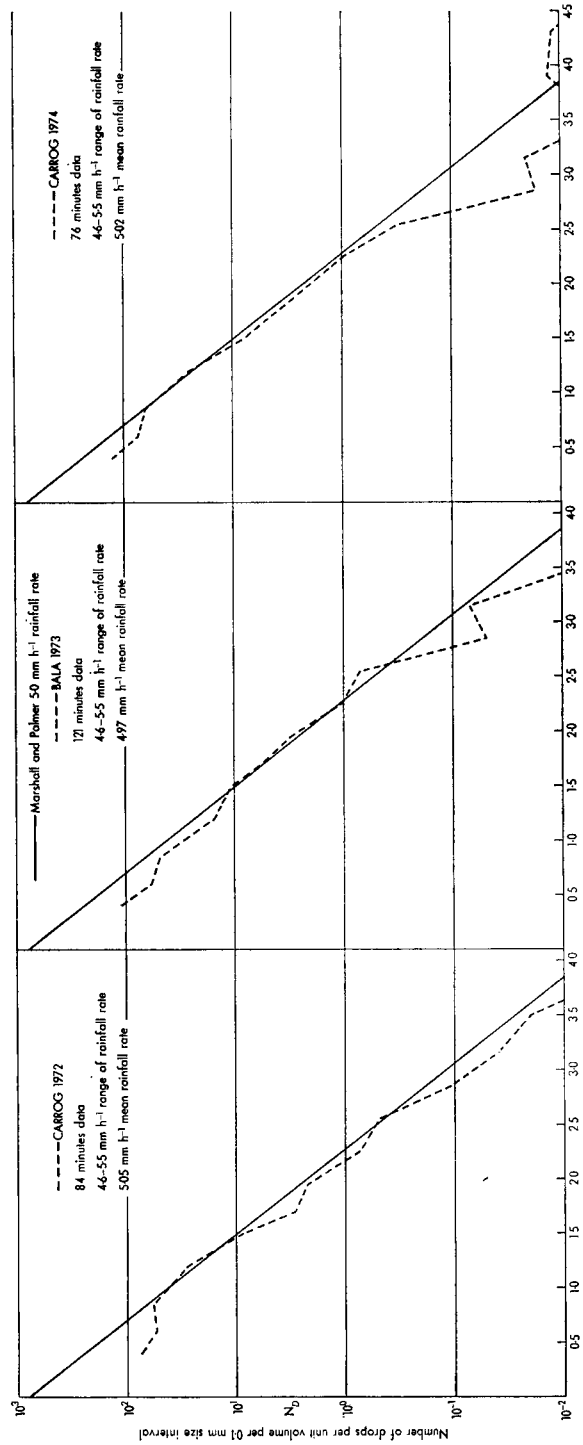

FIGURE 3—*continued*

measured deficiences become more marked at higher rainfall rates, as demonstrated in Figure 4, which shows the mean raindrop spectra for a number of rates from 0·95 mm h^{-1} to 38·3 mm h^{-1} at Carrog in 1972. (At the higher rates shown in Figure 4, data covering a very few minutes were included in the mean distributions.) The Marshall–Palmer distributions for 10 mm h^{-1} and 40 mm h^{-1} are also shown.

It is worth noting that the maximum numbers of drops at higher rainfall rates occur at about 1·2 mm diameter. Peaks in the drop-size distributions have been observed by Caton (1966) using Doppler radar in England as the measuring instrument and by Hardy (1963) in the United States using a photoelectric spectrometer, although their maxima were for drop diameters between 0·5 and 1·0 mm.

Some authors (e.g. Joss and Waldvogel (1970)) have subdivided their data into synoptic types and found different distributions for each. The data from North Wales have been treated in this manner, by selecting the periods of rainfall ahead of warm fronts, cold fronts and occlusions, rain associated with depressions (called cyclonic) and shower rain (including thunderstorms) and then finding the mean drop-size distributions for given rainfall rates. It was found that for given rain types and for fixed rates the mean drop spectra were very similar in the three years. An example is shown in Figure 5 where the drop-size distributions for rainfall rates of about 3 mm h^{-1} ahead of cold fronts are plotted for the three years, together with the Marshall–Palmer distribution for 3 mm h^{-1}. Once again the shortage of very small and very large drops can be seen.

Figure 6 shows the mean distributions for four weather types (occlusions did not provide sufficient data) at about 1 mm h^{-1} for Carrog 1972. It can be seen that for drops larger than 2 mm diameter, the four distributions are very similar. Below 2 mm there is a considerable difference between the types, in particular between frontal rain and showers. Surprisingly showers have more than twice as many small drops as warm frontal rain but only about 65 per cent as many medium-size drops.

The relationship between rainfall intensity and radar reflectivity

The parameters derived most frequently from drop-size distributions are the rate of rainfall R (in mm h^{-1}) and the radar reflectivity factor Z (in mm^6m^{-3}). It is widely accepted that an empirical relationship between them can be used to estimate rates of precipitation from radar measurements. However, the results of other authors around the world show that the relationship is highly variable and the use of a fixed equation could lead to serious error in the radar estimate of rainfall intensity. N_D and D are known for each drop-size distribution and since

$$Z \propto \sum_{i=1}^{16} N_{D,1} D^6 \text{ and } R \propto \sum_{i=1}^{16} N_{D,1} D^3,$$

values of Z and R maybe calculated for each distribution.

The relationship between Z and R is usually expressed in the form $Z = AR^B$. However, since R is here regarded as the dependent variable, the least-squares fit linear regression is of log R on log Z.

This procedure was used in the results which follow, the drop-size distributions being measured by the distrometer over 1-minute periods. Table III shows

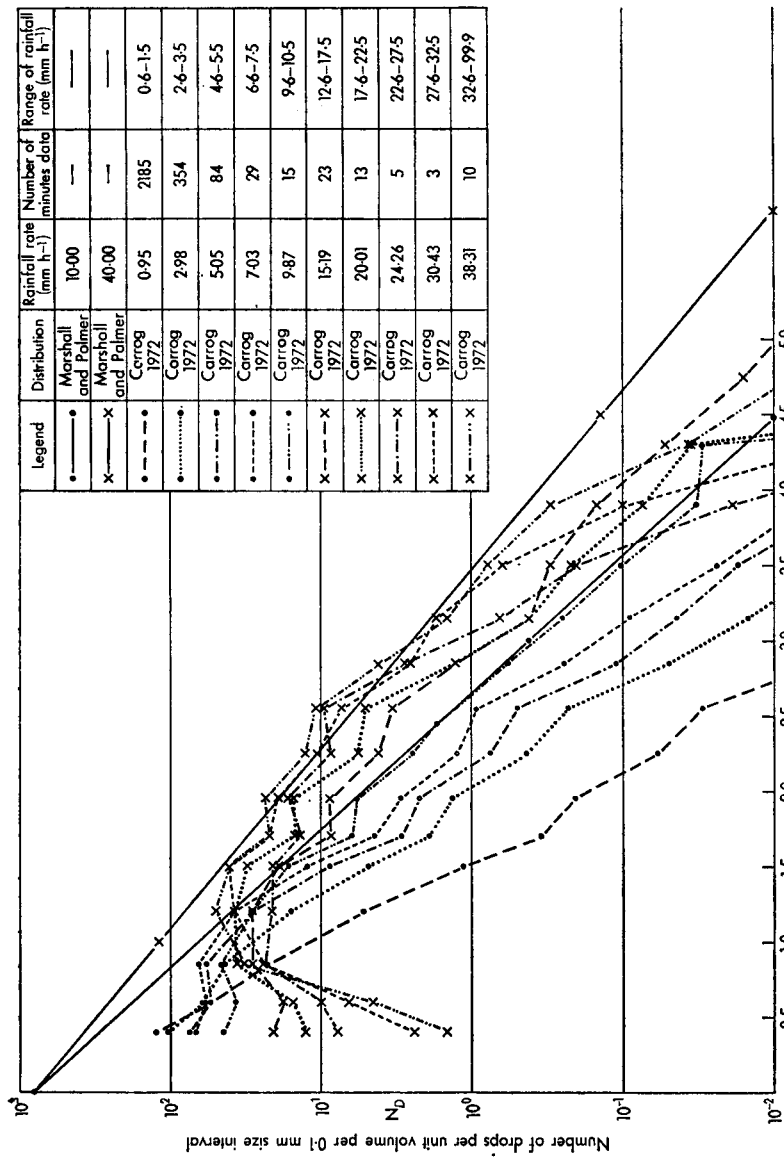

FIGURE 4—THE MEAN DROP SIZE DISTRIBUTIONS FOR A VARIETY OF RATES OF RAINFALL MEASURED AT CARROG IN 1972

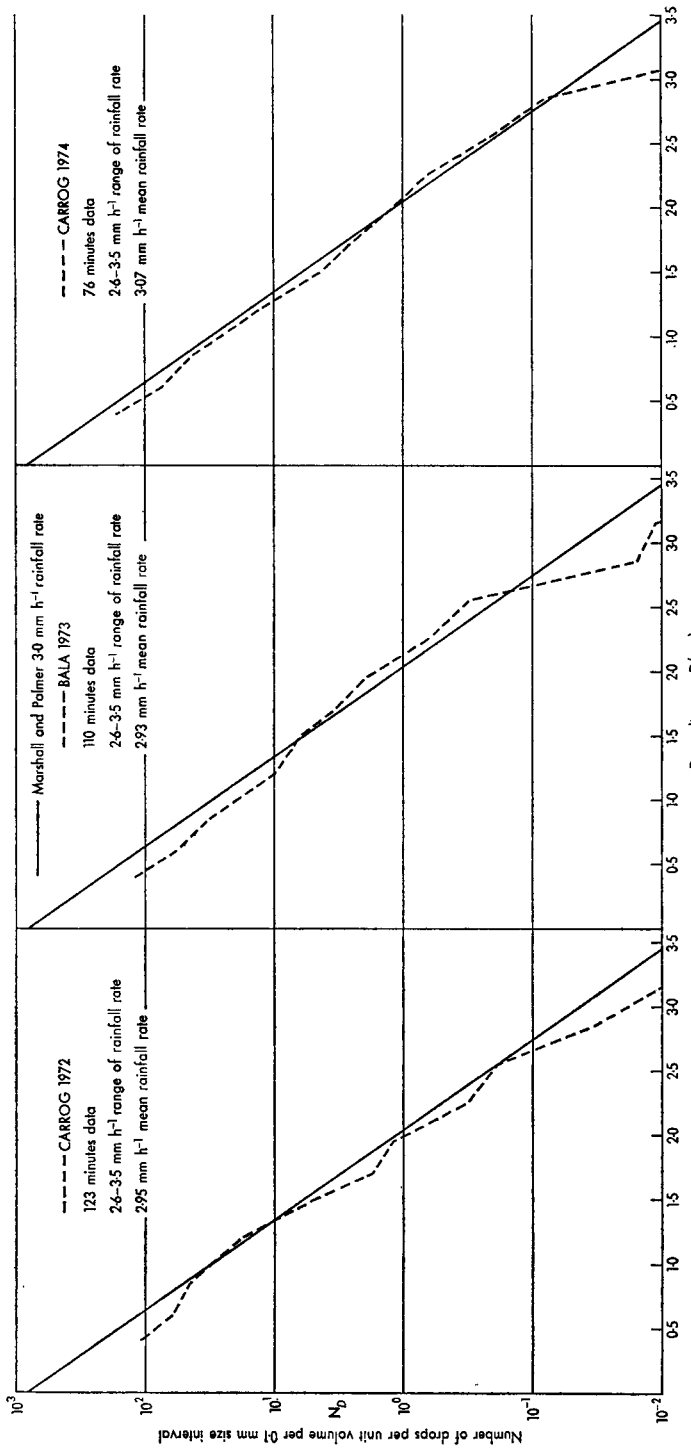

FIGURE 5—THE MEAN DROP SIZE DISTRIBUTIONS FOR RAIN AHEAD OF COLD FRONTS WITH AN INTENSITY OF ABOUT 3 mm h^{-1}

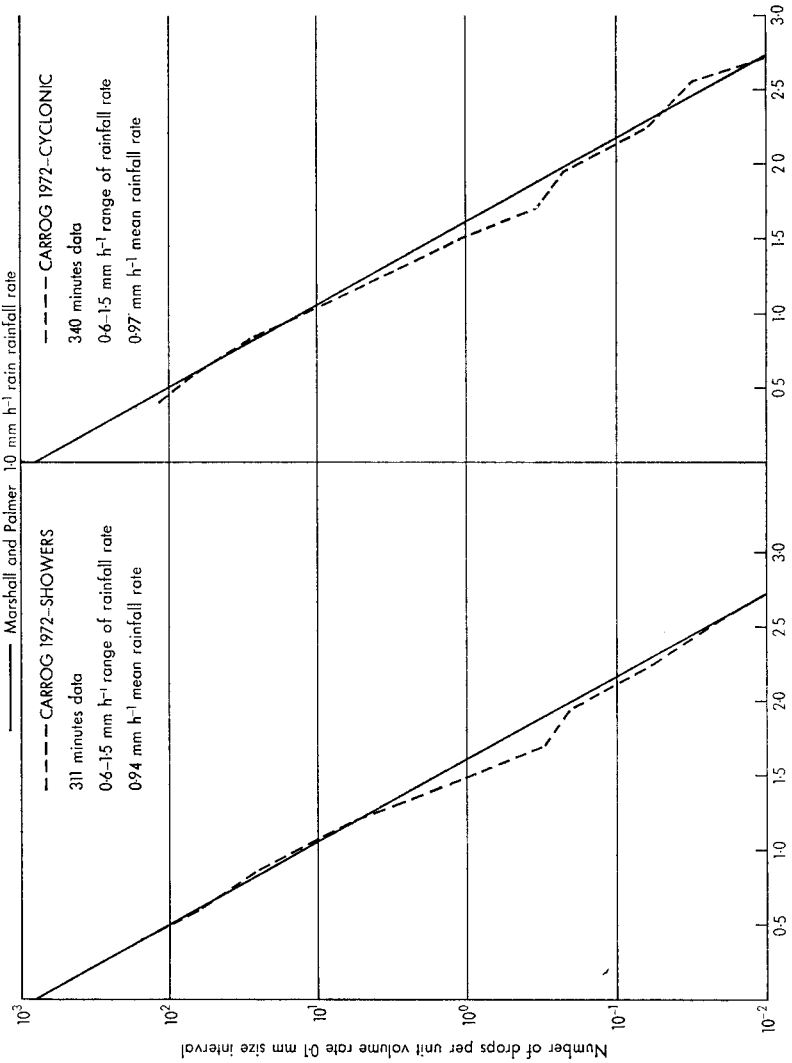

FIGURE 6—THE MEAN DROP SIZE DISTRIBUTIONS FOR VARIOUS RAINFALL TYPES WITH AN INTENSITY OF ABOUT 1 mm h^{-1} MEASURED AT CARROG IN 1972

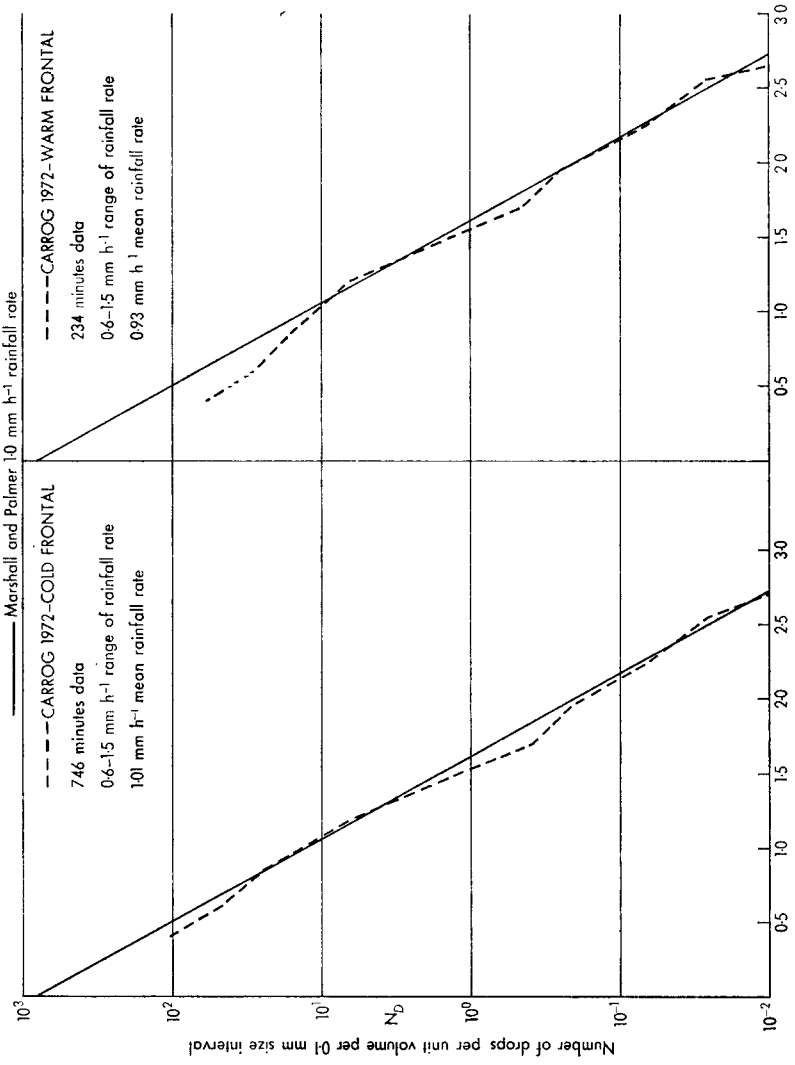

FIGURE 6—*continued*

the Z–R relationships in the three separate years calculated from log R on log Z linear regression for each minute when a rainfall rate of 0·1 mm h^{-1} or more was measured. The Table also shows the number of minutes of data (that is, the number of drop-size spectra used in each year's regression), the correlation coefficient, the range of measured rates of rainfall and the standard deviation of the constants A and B.

Z–R relationships for different parts of the world have been quoted by several authors, but although a least-squares method was used it is not always stated whether a regression of log Z on log R or vice versa was calculated. Table III includes results by both methods for comparison.

TABLE III—RADAR REFLECTIVITY (Z) AND RAINFALL RATE (R) RELATIONSHIPS

	Carrog 1972		Bala 1973		Carrog 1974	
	log R on log Z	log Z on log R	log R on log Z	log Z on log R	log R on log Z	log Z on log R
Number of raindrop-size distributions	9814		15 764		8473	
Range of rainfall rates	0·1 to 47·9		0·1 to 35·2		0·1 to 34·4	
Correlation coefficient	0·940		0·936		0·934	
A	249	206	258	206	241	197
Standard deviation of A	23	16	36	14	26	18
B	1·74	1·53	1·85	1·60	1·76	1·52
Standard deviation of B	0·026	0·021	0·111	0·058	0·075	0·020

It can be seen from Table III that the Z–R relationships for the three years are very similar, approximating to 250 $R^{1·8}$ for a log R on log Z regression, and 200 $R^{1·55}$ for a log Z on log R regression. (It was noted that about 1000 minutes were needed to obtain a consistent Z–R relationship in each year.)

There is considerable doubt which form of regression some past authors have used. The values of A and B in the $Z = AR^B$ relationship for North Wales calculated by a log Z on log R regression are very similar to those calculated by Marshall and Palmer (i.e. $Z = 220\ R^{1·6}$). However, calculating A and B from a log R on log Z regression results in higher values than those obtained by most other authors who used this form of regression, though theirs are based on a relatively small number of drop-size spectra when compared with the very large number of distributions shown in Table III.

It is apparent that, in order to improve the accuracy of measuring rainfall by radar methods over North Wales, a value of 1·8 for the exponent in the Z–R relationship should replace the value of 1·6 which is used at present (see Harrold *et alii*.)

A comparison of results has shown that using a value of 1·8 the improvement in accuracy at low rainfall rates ($<$1·0 mm h^{-1}) is about 10 per cent. At rainfall rates of most interest (i.e. $\geqslant$1 mm h^{-1}) only a small improvement of 2–3 per cent is achieved.

The lack of marked improvement is attributed to the fact that the radar samples aloft (about 300 m above ground at Carrog and 500 m above ground at Bala) whereas the relationships calculated in this paper are derived from drop-size distributions measured at ground level, which may have been affected by changes during the fall of the drops caused by low-level growth or evaporation, and size sorting by wind shears.

It has been proposed (Joss *et alii* (1970)) that more accurate measurements of rainfall can be made using radar if a different Z–R relationship is used for

various synoptic weather types. Table IV shows the average Z–R relationships in the three summers for five synoptic weather types, together with the number of drop-size distributions used and the range of rainfall rates.

TABLE IV—RADAR REFLECTIVITY (Z) AND RAINFALL RATE (R) RELATIONSHIPS (FROM LOG R ON LOG Z REGRESSION) FOR VARIOUS SYNOPTIC TYPES($Z=AR^B$)

	Carrog 1972		Bala 1973		Carrog 1974	
	A	*B*	*A*	*B*	*A*	*B*
Cold fronts	224	1·72	268	1·84	220	1·90
Number of distributions	2477		3814		1736	
Maximum rainfall rate*	12·3		7·4		11·1	
Warm fronts	264	1·60	229	1·79	260	1·66
Number of distributions	778		2257		1126	
Maximum rainfall rate	12·3		25·4		5·7	
Occlusions	422	2·01	194	1·95	316	1·65
Number of distributions	211 (only one storm)		805		1175	
Maximum rainfall rate	2·0		12·8		15·1	
Cyclonic rains	214	1·68	232	1·70	193	1·64
Number of distributions	1408		2613		1886	
Maximum rainfall rate	44·7		24·9		21·4	
Showers	234	1·70	254	1·79	235	1·64
Number of distributions	1320		942		1716	
Maximum rainfall rate	47·9		35·2		34·4	

* The minimum rainfall rate is 0·1 mm h^{-1}.

The results show that by reducing the data samples by subdivision there is a greater uncertainty in the Z–R relationship, and that any increase in accuracy which might be achieved would not justify the extra effort involved.

An attempt was made to relate the 'constants' A and B for the different synoptic types to low- and medium-level wind velocity but little correlation was established.

Table V shows the storm-to-storm variation of Z–R relationships, using Carrog 1972 as an example. A few storms with very small ranges of rainfall rates have been excluded.

It can be seen that if only a few storms, or parts of storms, had been used as the data sample on which to base the Z–R relationships a large error would be possible. Furthermore, if the mean Z–R relationship were to be applied to radar rainfall measurements, considerable day-to-day inaccuracy would result unless the radar system was additionally calibrated using a few widely spaced telemetering rain-gauges in the areas of interest (see Harrold *et alii*). The use of a number of distrometers to provide real-time Z–R relationships as an input to the radar would not seem to be feasible, because of the large amount of data processing involved.

Mean relationships between Z and R for all synoptic types for the three summers are illustrated in Figure 7.

The relationship of attenuation to rate of rainfall

Many authors (see for example Harrold (1974)) have stressed the importance of attenuation, caused by precipitation particles, on the transmission of radio signals at millimetric wavelengths. The ability of radar to measure precipitation is affected to a lesser extent by attenuation but nevertheless must be considered.

Gunn and East (1954) comprehensively reviewed the physics of attenuation and showed that it was derived from a complicated function dependent on the wavelength of the radiation, the temperature and the drop-size distribution.

TABLE V—STORM RADAR REFLECTIVITY (Z) AND RAINFALL RATE (R) RELATIONSHIPS AT CARROG 1972

Date	Number of drop-size distributions	Z–R relation A	B	Correlation coefficient	Range of rainfall rates (mm h^{-1})
Cold fronts					
29 Apr.	262	232	1·93	0·925	0·1– 3·4
25 May	62	197	1·48	0·964	0·1– 3·0
2 June	287	259	1·85	0·949	0·1– 6·2
8 June	60	258	1·51	0·976	0·1– 2·3
27 June	72	566	1·91	0·940	0·1– 3·3
4 Aug.	197	279	1·92	0·944	0·1–11·0
5 Aug.	37	92	1·65	0·977	0·1– 2·5
8 Aug.	73	114	1·31	0·980	0·1–12·3
17 Aug.	96	89	1·58	0·959	0·1–12·0
6 Sept.	188	191	1·78	0·945	0·1– 8·5
8 Sept.	324	190	1·61	0·906	0·1– 6·3
11 Oct.	414	231	1·64	0·944	0·1– 7·0
Warm fronts					
28 Apr.	286	296	1·75	0·952	0·1– 3·6
2 June	71	216	1·32	0·975	0·1– 2·3
7 Aug.	205	225	1·43	0·962	0·1–12·3
8 Sept.	142	379	1·59	0·967	0·1– 3·1
Occlusions					
20 June	211	422	2·01	0·906	0·1– 2·0
Cyclonic rains					
26 May	438	272	1·65	0·959	0·1– 9·3
9 June	255	320	1·52	0·961	0·1–44·7
1 Aug.	347	173	1·51	0·970	0·1–31·2
8 Aug.	368	119	1·51	0·958	0·1– 8·8
Showers and thunderstorms					
30 May	407	232	1·65	0·953	0·1–21·6
1 June	139	224	1·55	0·967	0·1–47·9
27 June	223	187	1·83	0·917	0·1– 4·4
6 July	67	293	1·76	0·903	0·1– 2·4
29 July	29	349	1·59	0·985	0·1–16·7
30 July	61	487	1·51	0·961	0·1– 3·5
9 Aug.	45	241	1·71	0·948	0·1–16·1
13 Aug.	68	165	1·59	0·970	0·1– 3·3
7 Sept.	91	204	1·72	0·924	0·1– 3·8
13 Sept.	164	237	1·71	0·953	0·1–11·7

They showed that at wavelengths which are long compared with the drop diameter the one-way attenuation (K), (i.e. half the total attenuation caused by precipitation *en route* to target and on return), in decibels per kilometre is given by

$$K = 0{\cdot}4343\,\Sigma Q_t,$$

where the summation is over one cubic metre and Q_t (the total absorption coefficient) is in square centimetres. Herman *et alii* (1961) have produced tables of normalized attenuation at 0°C ($=4Q_t/\pi D^2$) for a variety of wavelengths and drop sizes. From this quantity it is possible to calculate the attenuation caused by the measured drop-size distribution and hence to relate this to the rate of rainfall or radar reflectivity, both of which are derived from the distribution.

For each of six wavelengths frequently used in radar or radio work, the attenuation has been calculated in each minute when the rate of rainfall was 0·1 mm h^{-1} or more. A mean relationship of the type

$$K = ER^F$$

has been found by a least-squares linear regression of log K on log R. Table VI

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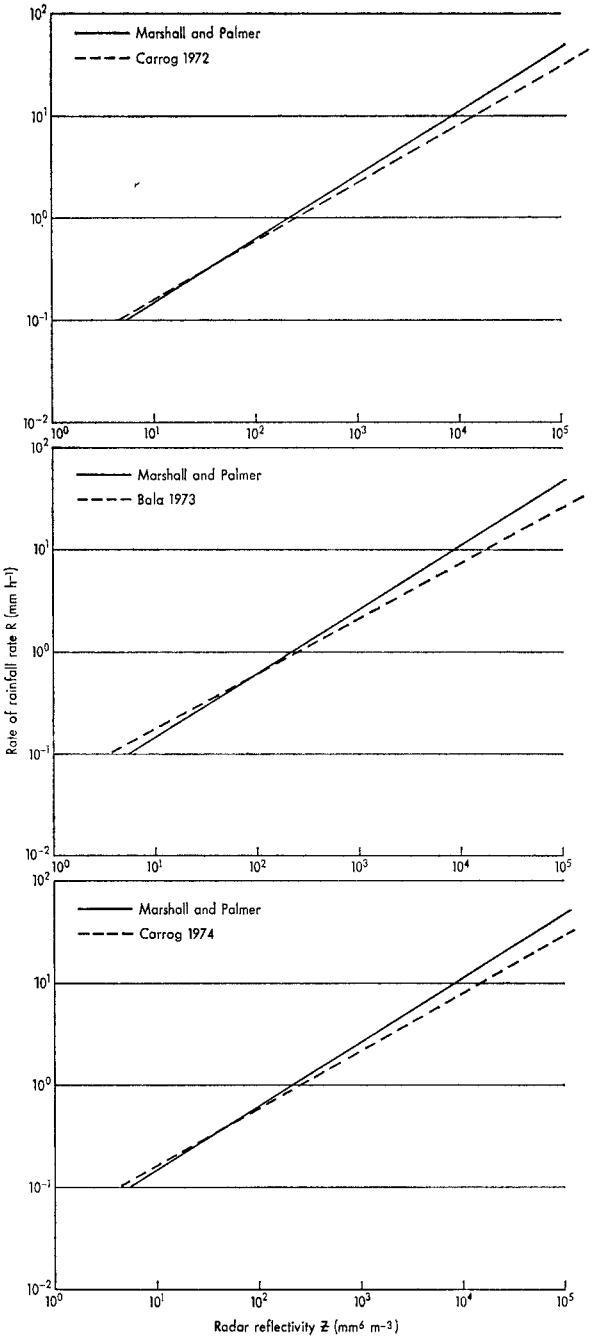

FIGURE 7—THE MEAN RELATIONSHIPS BETWEEN RATE OF RAINFALL AND RADAR REFLECTIVITY FACTOR FOR THE THREE SUMMERS

shows the results of these regression calculations and a comparison with those calculated by Wexler and Atlas (1963). In every case the correlation coefficient was 0·97 or higher.

TABLE VI—ATTENUATION (K) AND RAINFALL RATE (R) RELATIONSHIPS BASED ON ATTENUATION CONSTANTS E,F AT 0°C

Wavelength *cm*	Carrog 1972		Bala 1973		Carrog 1974		Marshall–Palmer after Wexler–Atlas	
	E	*F*	*E*	*F*	*E*	*F*	*E*	*F*
10·0	0·00071	0·98	0·00075	0·95	0·00070	0·99	0·00082	1·0
5·5	0·0026	0·94	0·0028	0·89	0·0026	0·92	0·0031	1·0
3·21	0·011	1·01	0·011	0·97	0·011	0·98	0·013	1·15
1·87	0·038	1·11	0·041	1·10	0·037	1·12	0·050	1·10
1·24	0·099	1·05	0·105	1·03	0·097	1·05	0·13	1·07
0·86	0·215	1·07	0·229	1·05	0·214	1·06	0·31	1·0

The attenuation constants were computed by Herman *et alii* using the Marshall and Palmer drop-size spectrum.

It can be seen that in each year the two 'constants' in the K–R relationships are very similar. At the wavelengths usually used for radar measurement of precipitation (5·5 to 10 cm) the attenuation is very small even at high rainfall rates. Using a 5·5-cm radar the attenuation at rainfall rates of 1 mm h^{-1} and 5 mm h^{-1} which are typical of North Wales result in attenuation of 0·0026 dB km^{-1} and 0·0118 dB km^{-1}.

The relationships derived from each year are also similar to those derived using a Marshall–Palmer distribution. The differences are attributed to the mean drop-size distributions described earlier showing slight variations from the Marshall–Palmer distribution at most rainfall rates.

The K–R relationships have been calculated using the full range of rainfall rates, although a high proportion of the data are for relatively low rates. For example, at Carrog in 1972, out of the 9814 drop spectra used, 9565 were for rates of rainfall of 5·0 mm h^{-1} or less. Thus the mean attenuation relationships obtained are most applicable at low rainfall rates, although the attenuation is more important at the higher rates, which fortunately occur infrequently. In an attempt to show how the attenuation relation is dependent on rainfall rate, the data have been divided into three overlapping ranges of rainfall rates, namely 0·1–5·0, 1·0–10·0 and greater than 5·0 mm h^{-1}, and the K–R relationships calculated by linear regression for drop-size distributions within these ranges. The results in the three years are very similar again, so only those for Carrog in 1972 are shown in Table VII.

Table VII shows that at wavelengths of 10 cm and 0·86 cm there is little to choose between the three regression equations. For the other wavelengths it can be seen that there is a tendency for the regression equations to have steeper slopes at higher rainfall rates, implying that the attenuation may become a more serious problem at very high rates than would be suggested by the original relationships shown in Table VI. A very large number of drop-size distributions are required, particularly at higher rates before the attenuation relationship can be defined with confidence at the rates of rainfall when it is more important.

Empirical relationships between attentuation (K) and radar reflectivity (Z) can be derived from the previously calculated Z–R and K–R relationships.

For example, at Carrog in 1972 for a wavelength of 5·5 cm

$$Z = 249R^{1\cdot74} \text{ and } K = 0\cdot0026R^{0\cdot94}$$

lead to the relationship

$$K = 1\cdot32 \times 10^{-4} Z^{0\cdot54}.$$

TABLE VII—ATTENUATION (K) AND RAINFALL RATE (R) RELATIONSHIPS OF FORM $K=ER^F$ AS A FUNCTION OF R AT CARROG 1972

Wavelength	Range of rainfall rates	Number of distributions	K–R relationship		Correlation coefficient
cm	*mm h*$^{-1}$		E	F	
10·0	0·1– 5·0	9565	0·00071	0·98	0·978
	1·0–10·0	2575	0·00072	0·90	0·971
	More than 5·0	249	0·00067	0·95	0·992
5·5	0·1– 5·0		0·0026	0·93	0·973
	1·0–10·0	As above	0·0025	0·95	0·976
	More than 5·0		0·0020	1·10	0·973
3·21	0·1– 5·0		0·0106	1·00	0·980
	1·0–10·0	As above	0·0102	1·06	0·974
	More than 5·0		0·0074	1·23	0·956
1·87	0·1– 5·0		0·0383	1·11	0·985
	1·0–10·0	As above	0·0380	1·09	0·978
	More than 5·0		0·0317	1·18	0·974
1·24	0·1– 5·0		0·0983	1·05	0·986
	1·0–10·0	As above	0·0966	1·07	0·983
	More than 5·0		0·0815	1·16	0·980
0·86	0·1– 5·0		0·216	1·07	0·987
	1·0–10·0	As above	0·215	1·06	0·986
	More than 5·0		0·209	1·07	0·990

OTHER METEOROLOGICAL PARAMETERS DERIVED FROM DROP-SIZE DISTRIBUTIONS

Although they are not frequently used in connection with radar rainfall measurements two other parameters, the liquid water content (M) and the median-volume drop diameter (D_0) can be calculated from the drop-size distribution.

The liquid water content is the mass of water (in grams) contained in 1 m^3 and is calculated by the summation of the masses of water contained in each drop category in 1 m^3;

$$\text{that is } M = \sum_{1\text{m}^3} N_D M_D \, \Delta D,$$

where M_D is the mass of a drop with a diameter in the range of D to $D + \Delta D$.

The liquid water content is related to the rate of rainfall by an empirical relationship of the type $M = GR^H$. The 'constants' can be derived by a least-squares linear regression of log M on log R, as in previous sections.

The liquid water content has been calculated for each drop-size distribution in the three years and the results of the linear regressions are shown in Table VIII. Also shown are the 'constants' in the relationship $Z = JM^P$ which can be derived from the Z–R and M–R relationships.

The median-volume drop diameter (D_0) has been defined by Atlas (1953) as that drop diameter which divides the drop distribution in such a way that half the liquid water content is contained in drops greater than D_0. As the liquid water content is related to the rate of rainfall by an empirical power relationship as above, it is reasonable to seek a similar relationship between the median-

TABLE VIII—LIQUID WATER CONTENT (M), RAINFALL RATE (R) AND RADAR REFLECTIVITY (Z) RELATIONSHIPS

Site	Number of distributions	$M=GR^H$ relationship (log M on log R) G	H	Correlation coefficient	$Z=JM^P$ relationship (direct calculation) J	P
Carrog 1972	9 814	0·0794	0·93	0·960	$2·79\times10^4$	1·86
Bala 1973	15 764	0·0863	0·90	0·946	$3·93\times10^4$	2·05
Carrog 1974	8 473	0·0805	0·93	0·958	$2·87\times10^4$	1·90

volume drop diameter and rainfall rate. The results of log D_0 on log R regressions for the three years' data are shown in Table IX. Atlas reported that the scatter about a line of the form $D_0 = SR^T$ (where D_0 is in mm and R in mm h^{-1}) is fairly large, and this is demonstrated by the rather low correlation coefficients in the Table.

TABLE IX—MEDIAN-VOLUME DROP DIAMETER (D_0) AND RAINFALL RATE (R) RELATIONSHIPS

Site	Number of distributions	$D_0=SR^T$ relationship S	T	Correlation coefficient
Carrog 1972	9 814	0·994	0·20	0·630
Bala 1973	15 764	0·961	0·24	0·677
Carrog 1974	8 473	0·962	0·21	0·623

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THE HEIGHT OF THE FREEZING LEVEL DURING RAINFALL OVER THE BRITISH ISLES

By C. G. COLLIER

SUMMARY

An analysis of the height of the freezing level over the British Isles is presented for November, January and March using the ten years of data 1964–73. The relationship of the spatial and temporal variations of this parameter to twelve-hour rainfall amount is investigated.

1. INTRODUCTION

Recent work on the measurement of rainfall using radar (see for example Harrold *et alii* (1974)) has demonstrated that radar rainfall measurements may be made with an accuracy of 15 to 20 per cent over periods of three hours, provided that the melting level is not intersected by the radar beam. When the melting level intersects the radar beam the accuracy is significantly decreased, since the presence of melting snow in the beam causes the power received at the aerial to be greater than that from rain at the same rate of precipitation (see Battan (1973)). Methods which attempt to correct the radar rainfall estimates when this occurs have been developed (see Harrold and Kitchingman (1975)). Nevertheless the errors that the melting level may introduce into the radar estimates cannot be completely removed. In order to examine how often this error may affect radar measurements in any part of the British Isles, a study is presented of the spatial variation of the height of the freezing level meaned over a ten-year period. The study is only concerned with the 0°C level. The centre of the melting layer is below this height, occasionally by several hundred metres (see Battan (1973)).

Previous work on the height of the freezing level by Murray (1950) has indicated its seasonal variations over the British Isles using six years of data 1942–47. The results are not related to rainfall, and therefore not directly applicable to the estimation of frequency of error occurrence due to melting-level effects in radar rainfall measurements.

In processing the data, when the temperature at the surface was less than 0°C the freezing level was taken as being at the surface. For cases in which a sounding had two or more heights at which the 0°C isotherm was intersected, only the lower height was considered, as this height is closest to the true height of the melting level relevant to radar measurement accuracy, as explained above. The freezing-level heights have been extracted from the radiosonde data recorded twice daily (00 and 12 GMT) at each of the routinely manned British Isles upper-air stations. The rainfall data have been extracted from the *Daily Weather Reports* for surface stations within 25 km of the upper-air stations. Twelve-hour rainfall totals spanning the times of the radiosonde ascents (the 'rainday' begins at 09 GMT) have been used in the analysis. Since the atmospheric structure varies considerably with time, the use of one ascent to represent 12 hours of rain imposes a severe limitation on the analysis, but more frequent upper-air temperature data are not available as routine.

2. Spatial variation of freezing-level height in winter

The variation of freezing-level height over the British Isles has been examined by Murray (1950) for each month of the year covering the period 1942–47. The ten years of data 1964–73 considered in the present study give mean freezing-level heights, use being made of all the data for the months of November, January and March, which agree well with those given in the earlier study. During the winter months the mean height of the freezing level, all data being considered without regard to rainfall amount in 12 hours, decreases uniformly from approximately 1100 metres over the south-west of the British Isles to approximately 600 metres over the northern tip of the Shetlands, Figure 1. In summer this lowering of freezing-level height is from the south-east to the north-east (see Murray (1950)), and the transition from summer to winter is illustrated by the month of November shown in Figure 1. The standard deviations about the mean values are between ±300 metres and ±800 metres, see Figure 2.

It is of interest to potential users of a radar system measuring rainfall to examine whether or not these mean maps are appropriate for all rainfall rates. The lower the height of the freezing level, the closer to the radar site its intersection with the beam, and therefore the greater the area of radar coverage affected by measurement errors introduced by its presence. Several ranges of 12-hour rainfall amount have been considered.

2.1 *Rainfall rate zero or 0·05 mm in 12 hours*

The distributions of mean freezing-level heights for zero or negligible rainfall in 12 hours are shown in Figure 3. Compared with the mean distribution for all rainfall rates (Figure 1), the freezing level is higher over the south-west of the British Isles in November, lower over the north-east of the British Isles in January, and slightly higher over the south-east of the British Isles in March. Table I gives the percentage frequency of occurrence of the freezing level below specified heights for three rainfall-rate ranges. This Table gives an indication of the amount of data available for each rainfall-rate classification. About 50 per cent of the data lie within this rainfall-rate range (i.e. 0–0·05 mm/12 hours).

2.2 *Rainfall rates between 0·05 mm in 12 hours and 5 mm in 12 hours*

In November and March the variation of mean freezing-level height for this class (Figure 4) resembles quite closely the mean pattern for all rainfall rates, but in January it is significantly different, showing a marked rise from the south. In January over Cornwall the mean height of the freezing level for this rainfall rate range is about 200 metres higher than given by the mean pattern (Figure 1), and this height increase is reflected throughout the British Isles. Approximately 45 per cent of the data fall within this rainfall-rate range (Table I).

2.3 *Rainfall rates between 5 mm in 12 hours and 10 mm in 12 hours*

Figure 5 shows a lowering in the mean height of the freezing level for this rainfall-rate range in both November and March compared with the distribution for all rainfall rates (Figure 1), in November from the north-west, and in March from the north over the eastern part of the British Isles. This effect is most marked in March when it produces a strong gradient of freezing-level height from east to west over England, and from north-east to south-west over Scotland. In March the mean freezing-level heights for this rainfall-rate range are 50 per cent lower than the mean values for all rainfall rates (Figure 1) over the

TABLE I—PERCENTAGE PROBABILITY OF THE 0°C LEVEL BEING BELOW SPECIFIED HEIGHTS (H_m) FOR RAINFALL AT SPECIFIED RATES (R mm/12 HOURS) DURING NOVEMBER, JANUARY AND MARCH

		metres																					
	H_m	500			1000			1500			2000			2500			3000			3500			4000		
	R mm/12 h	0/0·05	0·05–5	5–10	0/0·05	0·05–5	5–10	0/0·05	0·05–5	5–10	0/0·05	0·05–5	5–10	0/0·05	0·05–5	5–10	0/0·05	0·05–5	5–10	0/0·05	0·05–5	5–10	0/0·05	0·05–5	5–10
November	Camborne	0	1	0	10	11	2	18	24	4	22	31	5	27	36	6	35	41	7	40	46	7	41	47	7
	Valentia	1	0	0	7	19	2	15	35	4	17	41	4	22	47	6	27	52	7	32	54	7	32	55	7
	Crawley	9	3	0	25	8	1	35	17	2	39	21	3	44	25	4	54	29	4	61	31	4	63	31	4
	Hemsby	4	4	1	20	18	2	30	28	3	34	32	3	41	35	4	50	38	4	55	39	4	55	39	4
	Aughton	7	2	0	24	15	2	34	25	3	38	30	4	43	34	4	50	37	5	54	38	5	54	39	5
	Long Kesh	5	6	1	22	22	3	28	32	3	31	38	4	36	44	5	41	46	5	44	48	5	44	48	5
	Shanwell	14	4	1	37	17	1	47	23	2	51	27	2	55	30	2	62	31	2	64	32	2	64	32	2
	Stornoway	3	12	1	15	41	4	20	52	6	22	55	7	25	58	8	28	61	8	28	62	8	28	62	8
	Lerwick	8	15	2	15	46	6	18	55	7	20	58	8	22	60	9	23	62	9	24	63	9	24	63	9
January	Camborne	7	1	0	22	16	1	30	29	3	33	37	6	37	42	7	42	45	7	44	45	7	44	45	7
	Valentia	7	1	0	20	17	2	31	33	4	33	39	6	35	44	7	37	46	8	38	47	8	38	47	8
	Crawley	20	7	0	36	16	1	43	27	2	48	34	2	52	37	3	57	38	3	58	39	3	58	39	3
	Hemsby	19	10	0	36	20	1	44	31	1	50	36	1	54	39	1	57	41	1	58	41	1	58	41	1
	Aughton	21	5	0	35	18	1	45	28	3	50	32	4	54	35	5	58	35	5	59	35	5	59	35	5
	Long Kesh	14	7	1	30	23	2	37	36	3	41	41	4	44	44	5	47	46	5	47	46	5	47	46	5
	Shanwell	19	10	1	36	24	3	45	33	4	49	36	4	54	38	4	56	38	4	56	38	4	56	38	4
	Stornoway	9	11	1	25	34	3	34	49	4	36	53	4	37	55	5	38	55	5	38	55	5	38	55	5
	Lerwick	8	22	1	18	50	4	21	59	5	23	63	5	24	65	6	25	66	6	25	66	6	25	66	6
March	Camborne	8	2	0	29	14	1	41	23	2	50	31	3	55	33	3	60	34	3	62	34	3	62	34	3
	Valentia	3	1	0	23	22	1	34	35	2	40	42	3	45	43	3	49	44	3	50	44	3	50	44	3
	Crawley	17	3	1	38	12	1	54	20	1	60	24	2	67	25	3	69	25	3	71	25	3	72	25	3
	Hemsby	18	9	1	38	22	1	51	28	2	56	31	2	62	32	2	62	32	2	66	32	2	66	32	2
	Aughton	17	6	1	39	18	2	51	26	3	59	30	4	61	30	4	63	31	4	65	31	4	65	31	4
	Long Kesh	10	9	1	32	25	2	44	34	3	49	39	4	51	40	4	54	40	4	55	40	4	55	40	4
	Shanwell	20	9	1	46	21	1	58	25	1	63	27	1	68	28	1	70	28	1	71	28	1	71	28	1
	Stornoway	10	12	1	28	36	4	36	45	5	39	50	5	41	51	6	42	51	6	42	51	6	42	51	6
	Lerwick	14	21	4	29	41	5	35	49	7	36	52	7	37	53	8	37	53	8	37	53	8	37	53	8

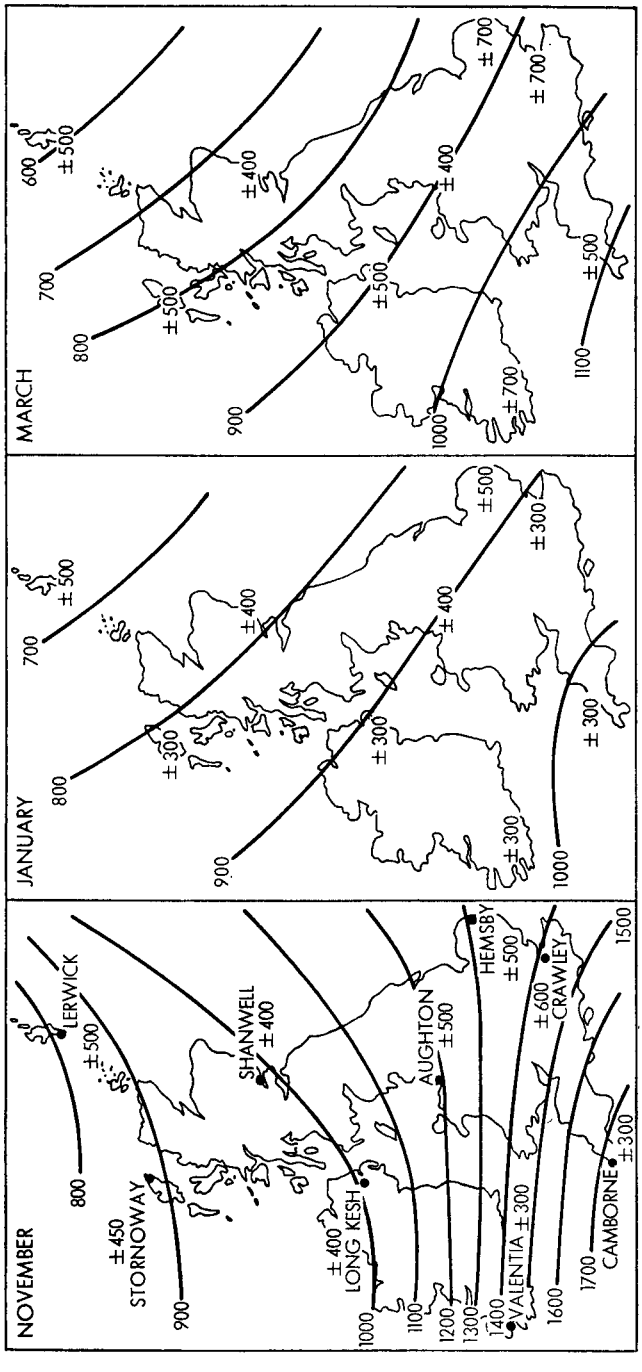

FIGURE 1—MEAN HEIGHT OF FREEZING LEVEL OVER THE BRITISH ISLES IN METRES FOR NOVEMBER, JANUARY AND MARCH 1964–73

The positions of the radiosonde stations used in the study are also shown, with an indication of the standard deviations of the heights at each station.

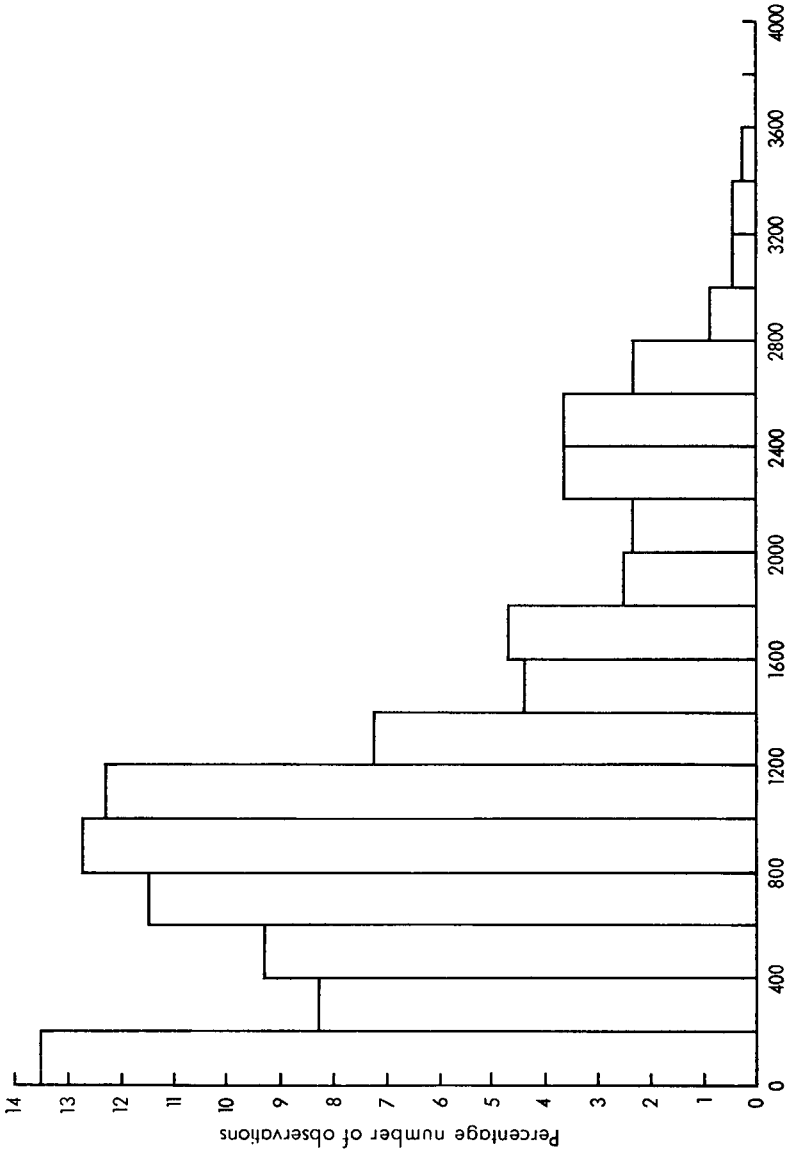

FIGURE 2—PERCENTAGE FREQUENCY OF HEIGHT OF FREEZING LEVEL IN JANUARY IN INTERVALS OF 200 m FOR AUGHTON 1964–73

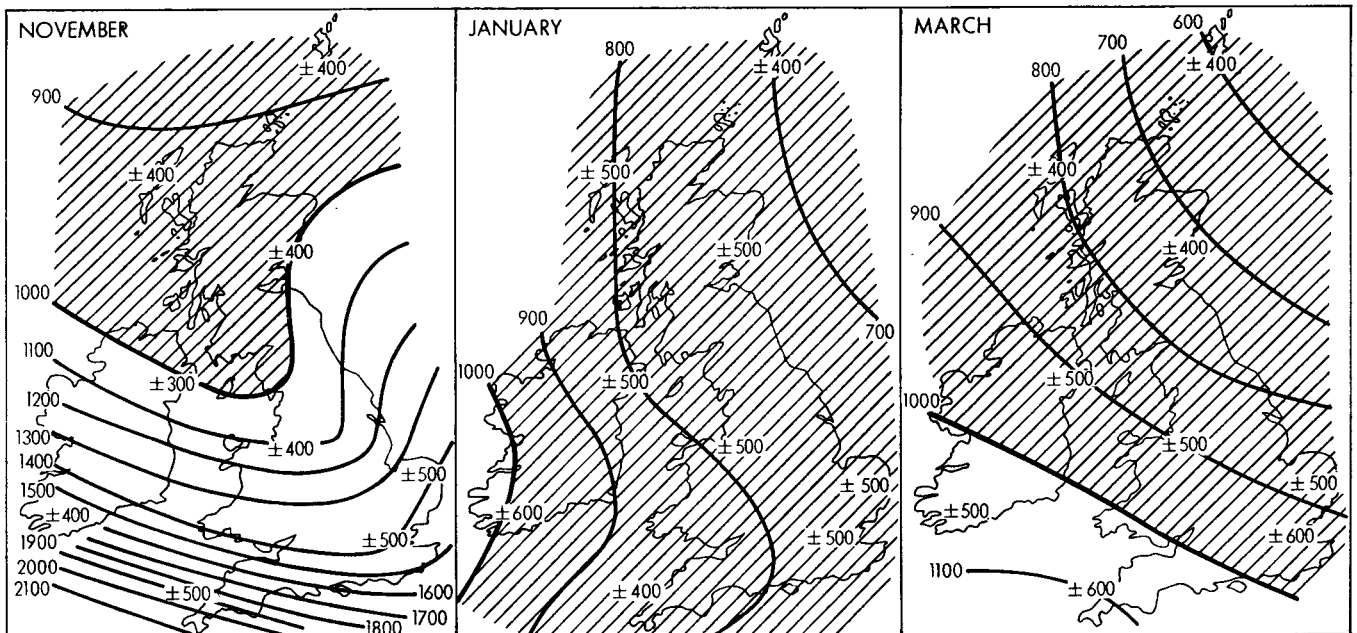

FIGURE 3—MEAN HEIGHT OF FREEZING LEVEL OVER THE BRITISH ISLES IN METRES FOR NOVEMBER, JANUARY AND MARCH FOR ZERO RAINFALL OR A TRACE (0·05 mm) IN 12 HOURS

The standard deviations of the heights at each radiosonde station are indicated. For a radar situated 100 m above sea level with a 1° wide beam and the beam axis elevated by 0·5° from the horizontal, the 0°C level intersects the beam at about 50 km range from the radar when it is at a height of 1 km. The stippling shows the areas within which the 0°C level would intersect the beam of this radar at ranges less than 50 km.

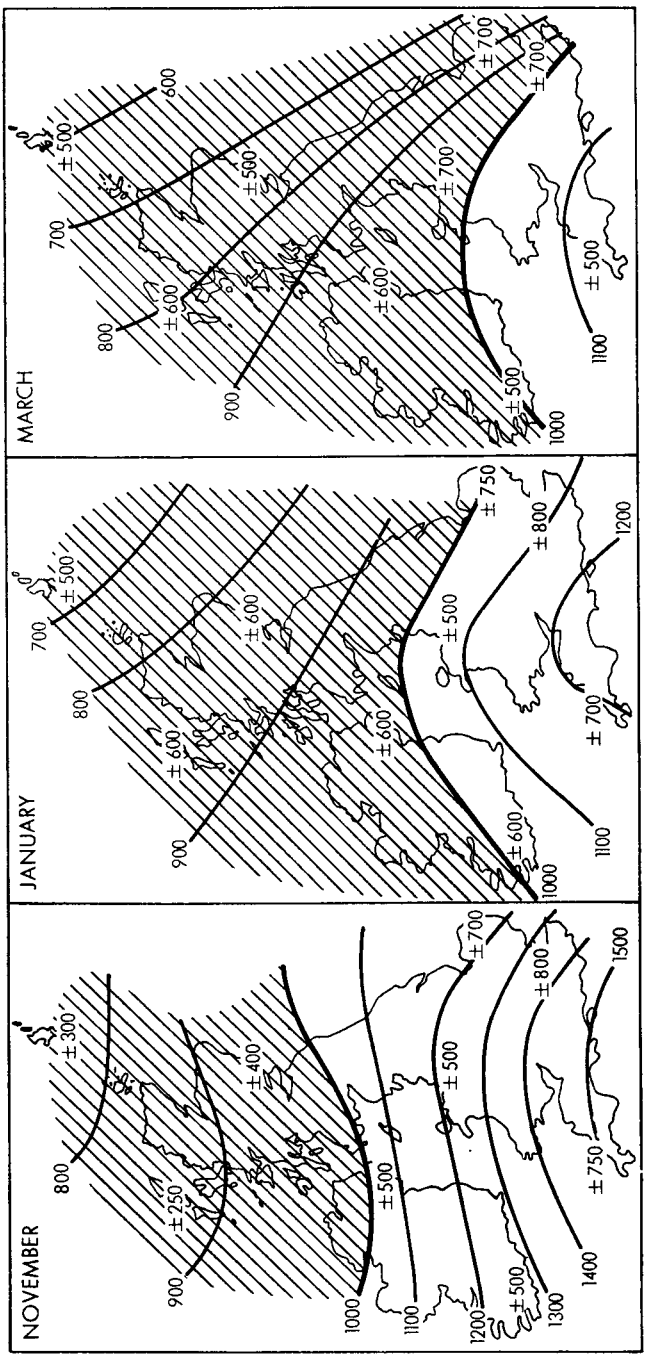

FIGURE 4—MEAN HEIGHT OF FREEZING LEVEL OVER THE BRITISH ISLES IN METRES FOR NOVEMBER, JANUARY AND MARCH FOR RAINFALL GREATER THAN A TRACE (0·05 mm) TO 5 mm IN 12 HOURS

See footnote for Figure 3.

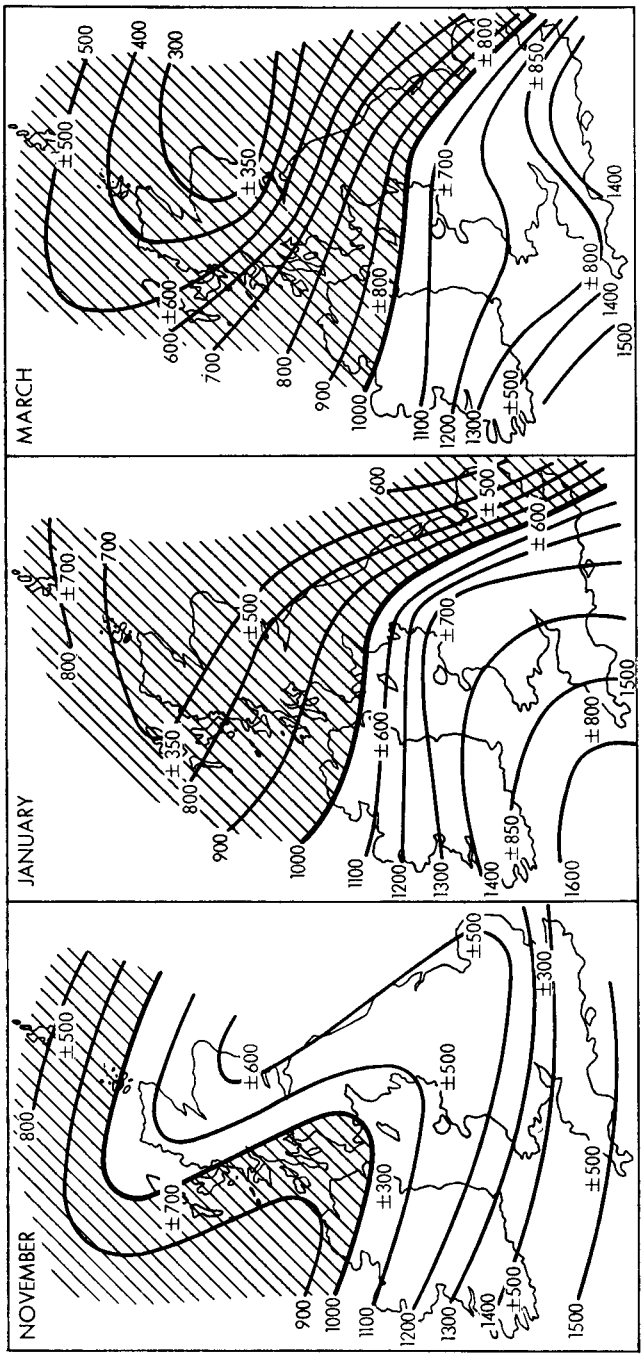

FIGURE 5—MEAN HEIGHT OF FREEZING LEVEL OVER THE BRITISH ISLES IN METRES FOR NOVEMBER, JANUARY AND MARCH FOR RAINFALL GREATER THAN 5 mm TO 10 mm IN 12 HOURS

See footnote for Figure 3.

eastern part of the British Isles. In January the tendency for the freezing level to rise is continued from the south-west, producing a mean pattern which changes by 700 metres across central England. Table I indicates that rainfall rates in this range make up less than 10 per cent of the data sample.

Since only a very small percentage (less than 3 per cent) of cases have rainfall rates greater than 10 mm/12 hours, it is felt that the data sample for these rainfall rates is too small to be discussed with any confidence.

3. Discussion

The freezing-level mean height patterns show large differences from one rainfall-rate range to another, but the significance of the changes depends upon the frequency with which the rainfall rates occur. Figure 6 shows the percentage frequency of 12-hour rainfall for Ringway Airport, Manchester (taken with the upper-air data for Aughton, Liverpool) for the period 1964–73. Fewer than 2 per cent of the data are composed of cases in which the 12-hour rainfall is greater than 10 mm, 4 per cent (of data) have rainfall in the range greater than 5 mm to 10 mm, and 60 per cent (of data) have zero rain or a trace (Section 2.3).

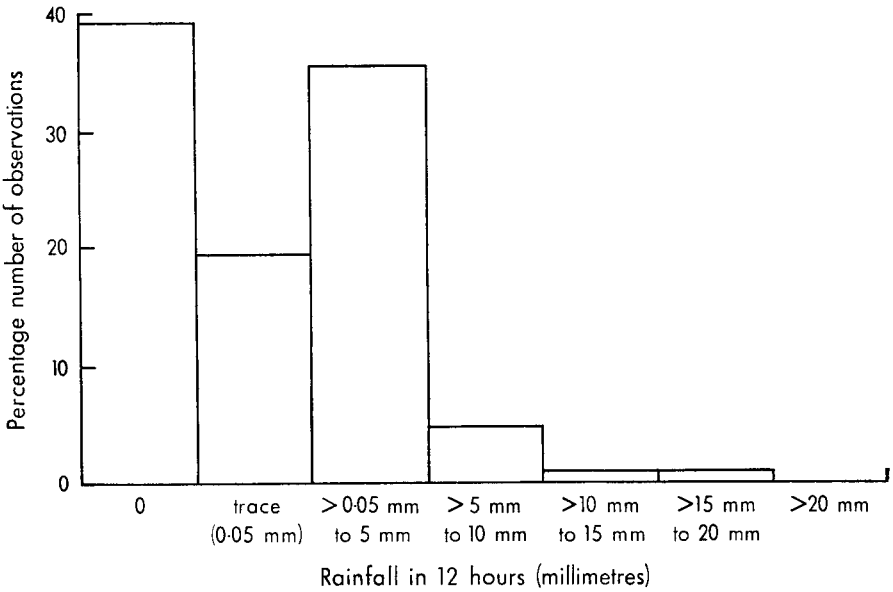

FIGURE 6—PERCENTAGE FREQUENCY OF 12-HOUR RAINFALL IN JANUARY FOR RINGWAY AIRPORT (TAKEN WITH THE UPPER-AIR DATA FOR AUGHTON), 1964–73

The marked differences from the mean patterns for the higher rainfall amounts may be related to the different frequencies of synoptic weather types through the winter months. However, there are only a small number of cases with rainfall rates in these ranges, and therefore the data sample is too small for any firm conclusions to be drawn from it. The frequency of daily weather types over the British Isles has been discussed by Lamb (1953, 1965), although the weather types are defined without reference to rainfall. Murray and Lewis (1966) extended this work, and suggested a system of indices which could be used to indicate the broad-scale circulation near the British Isles. In later papers Murray (1968, 1972) demonstrated the relationship of these indices to monthly

rainfall over England and Wales, and to monthly mean temperatures in central England. The tendency in winter months for low (high) rainfall to be associated with low (high) temperatures, and the tendency in the summer months for low (high) rainfall to be associated with high (low) temperatures were also discussed (Murray (1968)). This may account for the lowering of the freezing level in March (compared with the distribution for all rainfall rates (Figure 1) observed for the high rainfall-rate range (Figure 5) as March may be regarded as a transition month from winter to summer. The freezing level rises (compared with the distribution for all rainfall rates (Figure 1) for the high rainfall-rate ranges in January, a winter month.

It is not the purpose of this paper to seek detailed correlations between rainfall, height of the freezing level and synoptic weather type as represented by the indices by Murray and Lewis (1966). To do so would require a much more detailed discussion than has been presented in this paper. The above represents a suggestion where the explanation of the form of Figures 3 to 5 may lie.

Table I gives the percentage frequency with which the 0°C level is below a specified height, for a particular rainfall rate. The effects of latitude and season are apparent in the Table. Figures 3 to 5 and Table I may be used to estimate the mean distance, for any radar site in the British Isles, at which the radar beam intersects the freezing level, for various ranges of 12-hour rainfall amount in winter. For a radar situated 100 m above sea level with a 1° wide beam and the beam axis elevated by 0·5° from the horizontal, the 0°C level intersects the beam at about 50 km range from the radar when it is at a height of 1 km. The stippling on Figures 3 and 4 shows the areas where the 0°C level would intersect the beam of this radar at ranges less than 50 km.

Figure 7 indicates the mean percentage number of occasions with the 12-hour rainfall amount in the range 0·05 mm to 5 mm, when the 0°C level would intersect the beam of a radar, elevated by 0·5° from the horizontal, within 50 km of the radar site. The radar is assumed to be situated 100 m above sea level at each of the radiosonde sites, and at each site on the maps the upper figure is the average number of occurrences in the month with rainfall in the range 0·05 mm to 5 mm in 12 hours. The lower figure at the stations is the average number of occurrences in the month with rainfall in the range 0·05 mm to 5 mm in 12 hours when the 0°C level intersects the radar beam within 50 km of the radar site. These maps enable the mean percentage amount of data, in the rainfall range 0·05 mm to 5 mm in 12 hours, likely to be effected by measurement errors introduced when the 0°C level intersects the radar beam within 50 km of the radar site, to be derived for any part of the British Isles. Ten years of data have been used to produce Figure 7, 1964–73, and it must be stressed that any one year may differ markedly from average. For example, for the C-band Llandegla radar used in the Dee Weather radar Project (see Collier *et alii*, 1975) (400 m above sea level) in January 1974, 61 per cent of the radar data collected were affected by measurement errors introduced by the presence of the melting level in the beam within 50 km of the radar site. However, in March 1974, only 28 per cent of the radar data were affected. The corresponding mean figures derived from Figure 7 are 50 per cent in January and 60 per cent in March.

Given the frequency distribution of the rainfall-rate ranges near a particular radar site, the mean temporal variations of the range at which the radar beam intersects the 0°C level may be obtained. For example, for the Llandegla C-band radar, the data given in Table I for Aughton may be used assuming a beam

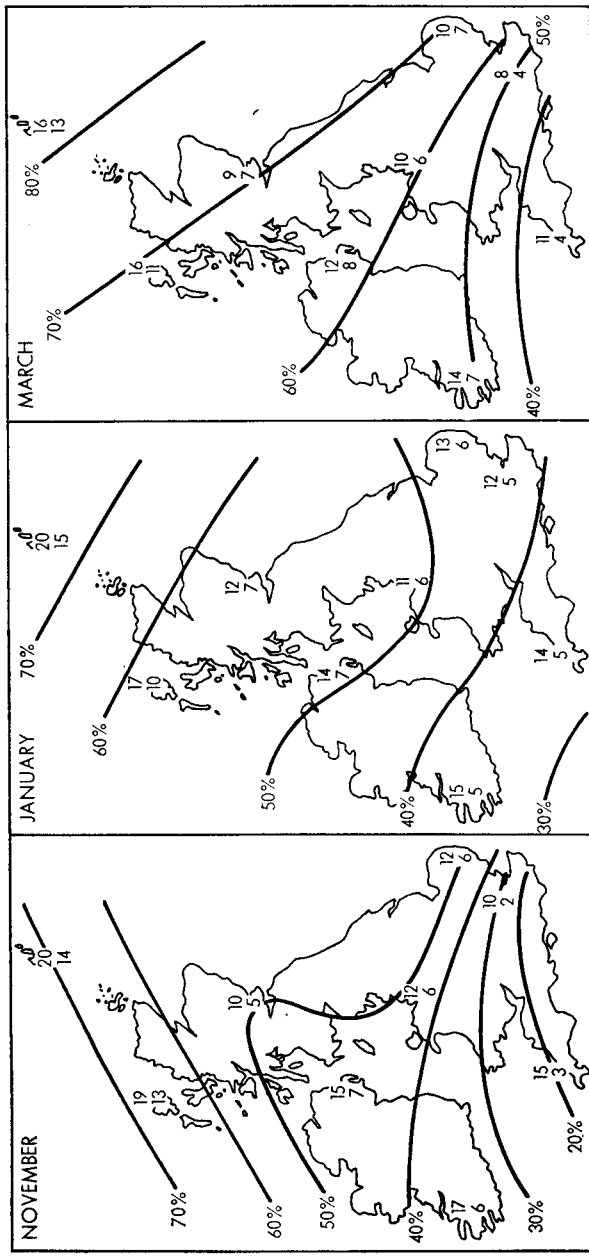

FIGURE 7—10-YEAR AVERAGE PERCENTAGES OF OCCASIONS ON WHICH THE MELTING LEVEL INTERSECTS THE RADAR BEAM, ELEVATED AT 0·5°, AT A DISTANCE OF 50 km OR LESS

The height of the radar site is taken as 100 m above sea level. The 12-hour rainfall amount near the radar is between 0·05 mm and 5 mm. The upper figure at each radiosonde station is the mean number of occurrences in the month with rainfall in the given range, and the lower figure is the mean number of occurrences in the month with rainfall in the given range, when the 0°C level intersects the radar beam within 50 km of the radar site.

elevation of 0·5°. The mean freezing-level height over North Wales for rainfall rates between 0·05 and 5 mm in 12 hours in November is 1250 metres, in January is 1100 metres, and in March is 1000 metres. On average, rainfall rates in this range occur on 7 days per month (corresponding approximately to a percentage probability of 35 per cent) in winter, and on 4 of those days or less the freezing level will be intersected at a distance of about 41 km (corresponding to a freezing-level height of 1250 metres which occurs with a percentage probability of about 20 per cent for this rainfall-rate range) in November, 30 km in January and 27 km in March. However, for a rainfall-rate range of 5 mm in 12 hours to 10 mm in 12 hours, the mean heights are 1300 metres in November, 1100 metres in January and 950 metres in March. On average, rainfall rates within this range occur on only 1 day per month or less, and on half of this day the freezing level will be intersected at a distance of about 45 km in November, 36 km in January and 30 km in March.

4. Conclusion

The variation of the height of the freezing level over the British Isles in winter, shown in Figure 1 for all rainfall rates, reflects the dependence of this parameter on latitude and season. However, there is a relationship between mean freezing-level height and 12-hour rainfall amount.

The data presented in this paper allow mean estimates to be made of the distance from a radar site at which the freezing level intersects the radar beam in winter. The percentage amount of radar data with 12-hour rainfall in a given range affected by melting level errors may also be estimated.

5. Acknowledgements

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NOTICES

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